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ABSTRACT

The full proceedings are provided here of a conference of 40 teachers, educational researchers, and scientists from both the public and private sectors that centered on the future of computers in education and the research required to realize the computer's educational potential. A summary of the research issues considered and suggested means for stimulating and supporting proposed basic and prototype research activities is followed by the Chairmen's Report. The invited papers are then presented: (1) "The Computer Age," by Herbert A. Simon; (2) "Technologies for Learning," by Raj Reddy; (3) "Paradigms for Computer-Based Education," by Alan M. Lesgold; (4) "Research on Science Education," by Jill H. Larkin; (5) "Research on Mathematics Education," by Robert B. Davis; (6) "Teaching Mathematics," by Steve Davis; (7) "The Mathematics Curriculum K-12," by Henry O. Pollack; (8) "Teaching Science," by Jim Minstrell; (9) "Research on Reading Education," by Richard C. Anderson; (10) "Research on Writing Education," by Robert Gundlach; (11) "Teaching Reading," by Catherine Copeland; (12) "Teaching Writing," by Brooke Workman; and (15) "Literacy," by E. D. Hirsch, Jr. Reports of the Conference Committees on Mathematics and Science (Frederick Reif) and Reading and Writing (Alan M. Lesgold) conclude the report. (LMM)

Computers in Education:

Realizing the Potential

Report of a Research Conference

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COMPUTERS IN EDUCATION
REALIZING THE POTENTIAL

Report of a Research Conference

Pittsburgh, Pennsylvania

November 20-24, 1982

Alan M. Lesgold
and
Frederick Reif
Chairmen

U.S. Department of Education
Terrel H. Bell, Secretary

Office of Educational Research and Improvement
Donald J. Senese, Assistant Secretary

August 1983

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FOREWORD

Today we no longer ask, "Will computers be used in the schools?" We know that they are, and that they are being purchased by schools faster than we can keep count. Indeed, surveys of computers in schools are outdated by the time they are published. The computer has excited administrators, teachers, students, and parents in a way that no other educational tool, theory, or curriculum has before.

With this rapid adoption of microcomputers, more questions have been raised than have answers, however. What are the optimum school uses to which microcomputers can and should be put? What does research in learning theory, cognition, motivation and artificial intelligence have to say about how computers affect learning? What approaches can be taken in various disciplines to maximize the computer's effectiveness? How can schools most efficiently integrate these findings into their instructional programs?

It was with these questions in mind that the Department of Education invited a group of educational researchers and practitioners to the research conference "Computers in Education: Realizing the Potential" at the University of Pittsburgh in late November 1982. The results of that conference are summarized in this Chairmen's Report.

We are pleased to share the results of this important research conference with the educational community. On behalf of the Department of Education, I would like to extend our sincere thanks to those participating scholars and educational practitioners who brought so much wisdom, experience, and common sense to the conduct of this conference.

Donald J. Senese
Assistant Secretary for Educational
Research and Improvement
U.S. Department of Education

CHAIRMEN'S PREFACE

In November, 1982, The Department of Education invited forty people to a special conference on the future of computers in education and the research needed to realize the computer's potential. There were computer scientists, psychologists, other educational researchers, teachers, school administrators and parent representatives. A set of invited papers (published in the proceedings of this conference) and an excellent series of software demonstrations provided a good foundation for our discussions.

The participants discovered quickly that they agreed on a number of issues. The computer is perhaps the most exciting potential source of educational improvement in centuries. Although most currently available applications for schools are mediocre, the possibilities for significant uses are impressive. The agenda for research, our primary charge, was easily agreed upon. Many of us also stressed the need to develop teachers' abilities to use computers and the need to make rich computer environments accessible to teachers, parents and children of all socioeconomic levels. Many of the participants worked extremely hard to build a coherent set of recommendations; some attended sessions all day and drafted recommendations a good part of the night. Without those efforts, this report would have been extremely difficult to write.

This report benefited from the dedication of many people. The Secretary of Education, Terrel Bell, and Assistant Secretary Donald Senese showed great concern for issues of educational technology and kept us motivated in our efforts. We hope that we and the other participants have produced recommendations they can use. Arthur Melmed, John Mays, Susan Chipman, and Joseph Psotka filled the difficult multiple roles of government representatives, conference organizers, critical reviewers, and colleagues. Jill Larkin and Jean Dexheimer helped lay the groundwork for the meetings and produced an excellent state-of-the-art sampling of instructional computer software. Ms. Dexheimer and Richard Wolf were responsible for several rooms full of reliably-working computers for demonstrations. The University of Pittsburgh and Carnegie-Mellon University provided excellent facilities for the meetings. Rebecca Freeland, Gail Kratt, Steve Roth, and Carol White provided the highest level of staff support at the conference, and Ms. White provided technical editing for this report. The summary was prepared with the help of John Mays, and Kathleen Fulton coordinated all the details regarding publication of the full report. We thank them all and hope that their efforts result in the kinds of exciting educational improvements that we believe are possible.

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SUMMARY

INTRODUCTION

The computer is a one-in-several centuries innovation. The low cost and wide availability of the computer, combined with other technological and scientific advances, is changing the nature of business, industry, and everyday life.

Preparing students for this new world makes strong demands on education, at a time when the cost of education is rising more rapidly than other prices.

Fortunately the computer, combined with new knowledge of human thinking and learning, provides new means for meeting these needs and eventually for increasing the productivity of education.

Realizing the full potential of the computer in education requires ground-breaking research that will allow educators and manufacturers to proceed confidently in the development of advanced computer-based materials for the schools. Earlier Federally supported research provided the basis for the computer-aided instruction of the last decade and a half. Another such research program is now needed to take advantage of the vastly increased capability of affordable computers.

This report proposes a variety of research activities needed to provide a basis for achieving the potential of the computer in education through refining basic principles for computer-enhanced instruction and demonstrating the effectiveness of these principles.

NEEDS AND OPPORTUNITIES

Educating for a High Technology Future

We appear to be raising a generation of Americans many of whom lack the understanding and the skills to participate fully in the technological world in which they live and work.

The scientists and engineers who will provide the new knowledge and ideas required to maintain our world leadership will need increasingly sophisticated education in science and mathematics. Many others must be given the background necessary to build, maintain, and use the technological devices that are increasingly permeating business and industry. All of us need new knowledge to deal adequately with the products of technology in daily life and to participate as citizens in the increasing number of decisions involving science and technology.

The rapid changes brought about by science and technology and the rapid expansion of knowledge require new emphases in education. The well-balanced citizen and worker will need skills in using computers, selecting appropriate information, reasoning abstractly, solving problems and learning independently.

This demand for excellence, and for new educational forms and content, comes at a time when many good teachers are abandoning education for higher-salaried fields, and the better students are tending not to enter the teaching profession. Shrinking budgets make schools reluctant to purchase courseware that has not been proven in other schools, and make the school market an unattractive one for firms which might develop sophisticated computer-based teaching materials.

Potentials for Improvement

Recent technological and scientific advances create a unique opportunity for meeting these new educational demands.

The cost of computers is falling rapidly. The first dedicated computer used for instruction in a school cost a third of a million dollars. Current systems with good graphics cost about a thousand dollars. It appears likely, projecting trends in hardware and software technologies, that computational power equivalent to that of present day super-computers will be available in a microprocessor system for under $100 by 1990. Videodisc systems now available for under a $1000 allow almost instantaneous access to 54,000 full color images recorded on a disc costing $20 to $30.

In recent years there has come into being a new cognitive science. This interdisciplinary field involves the psychology of human comprehension, problem-solving, and learning; artificial intelligence (the science of computer systems that exhibit understanding and problem-solving skills); linguistics; and other related fields. Cognitive science is beginning to provide a firm foundation of knowledge about how human beings comprehend when they read and observe, how they go about solving problems, and how they can best be helped to become skilled in these and other higher-level intellectual activities.

By exploiting the new technologies and building on new insights into human intelligence and its development, education can be made much more effective and able to meet the new challenges it faces. The following are examples of major educational opportunities presented by the computer.

- Tutoring. The computer can be an excellent tutor. It is patient and can adapt to students' individual capabilities. Recent progress in developing computer-based "expert systems" is being extended to tutoring, and the ability of computers to "understand" ordinary written and even spoken language is being improved. Thus we can expect tutoring systems to have increasingly refined teaching strategies and capabilities to communicate with students.

- Exploratory learning environments. Computers can be used to provide new "learning environments" in which students can perform simulated experiments quickly, inexpensively, and without danger. They can explore new ideas and "learn by doing" in contexts that are tailored to their current capabilities.

- Diagnosis. Computers can be used to diagnose an individual student's current knowledge, thinking strategies, and learning capabilities. This assistance can be very helpful to teachers in devising appropriate learning activities for the student.

- Networks. By connecting computers inexpensively through new telecommunications technologies, it is possible to create intellectual communities without regard to participants' physical locations. For example, students who are handicapped, have special interests, or need gifted colleagues could interact with other students with similar needs through a computer network. Schools without a major library could be given access to an electronic information bank. Teachers could improve their teaching by sharing ideas and experience with one another.

- Tools for students and teachers. Computers are powerful intellectual tools. In addition to performing calculations, they are becoming able to manipulate equations, they can facilitate writing and encourage the sort of revision that is essential to developing precision of language; they can retrieve information from large data bases and provide instant access to the meaning of words and concepts. These capabilities allow shifting of emphasis from routine skills to more sophisticated thinking processes which will be more necessary in the future.

- Game technologies. Computer games can provide motivation and practice, although their effects on children's cognitive and affective development require further study. Arcade game techniques are already being used in a few areas of military training, with promising results.

- Helping with administrative tasks. Teachers are inundated with record-keeping chores which use time and energy that could be spent in teaching. Computers can handle many of these routinely, freeing teachers to teach.

REALIZING THE POTENTIAL

The possibilities we have described are based on our knowledge of recent developments in artificial intelligence and other areas of computer science, in the cognitive psychology of instruction, and in computer technology. However, considerably more work is essential for these possibilities to be realized. The basic conclusion of this conference is that striking improvement in the quality and productivity of education through computer-based instructional systems is attainable, but only with a national investment that continues reliably for several years.

Research undertaken to exploit the educational applications of computers can also guard against the discrediting of promising ideas by poor implementation and against harmful use of technology. Education in the computer age must not result in students' being isolated from one another by electronics, bored or confused by poorly designed software, or rendered passive by systems which do not promote exploration or initiative.

We recommend that the Federal government support a coherent effort to build exploratory prototypes of the intelligent instructional systems that are possible. Such prototypes can provide:

- the necessary knowledge and experience for subsequent development of instructional systems and materials by private industry and schools,
- laboratory settings for needed fundamental research on:
  - processes involved in skilled reading, writing, mathematics, science, and other intellectual activities,
  - new ways to adapt instruction to individual differences in aptitude and progress in learning, and
  - the psychology of student and teacher interaction with automated instructional systems.

Prototype Research

The substantial educational promise in computer technology and the cognitive sciences comes largely from laboratory research and from technologies that have yet to be fully exploited in classrooms. The next step is prototype research, in which the basic principles are refined by trying them out in pilot applications. To be most useful, prototype research should allow teachers, school administrators, and students to contribute their own ideas to the work. Projects should be conceived as a partnership involving researchers, a school system, and in some cases private companies.

Examples of prototypes to be explored, of the sorts listed in an earlier section above, are described in some detail in the Chairmen's Report.

Associated Fundamental Research

If we are to realize the potential of computer technology for helping students achieve high levels of capability in mathematics, science, reading, and writing, we need fundamental research of several kinds. We limit our recommendations here to specific activities from which we expect shorter-term pay-off: enhanced design principles for human-computer systems for education. We also strongly urge that the research integrate the insights of teachers and other educators with those of scientists. The development of useful systems will rest on the twin pillars of practical and theoretical knowledge.

Research on Cognitive Issues

Various fruitful lines of research are greatly improving our understanding of the thinking processes needed for learning sophisticated concepts and for solving problems. This research must be continued in the context of computer-based education. Examples include:

- Expert and novice thinking. Recent studies in science education have revealed that students approach learning tasks with many prior conceptions, based on their life experience, which can be obstacles to new learning. These conceptions are very resistant to change. We need to understand why students' conceptions persevere so strongly and how they can best be modified.

- Comprehension and writing strategies. Even secondary students have difficulty summarizing texts, defining main points, skimming texts to abstract information quickly, taking notes, and planning and revising compositions. We envision computer aids that will help students develop these higher-level skills, but improved understanding is first required of the cognitive processes underlying advanced reading and writing.

- Knowledge structure. Recent work in cognitive science reveals that the manner in which knowledge is structured in a person's mind can greatly affect the ease with which it can be used in various intellectual tasks. We need to know more about how we should organize and teach basic knowledge so that it is easier to recall when needed to solve a problem and easier to add to, as more experience and knowledge are gained.

- Mental models. "Mental models" are relatively simple conceptual schemes developed by individuals to explain, predict, and control phenomena they encounter. We need greater understanding of mental models people have for various intellectual tasks, as such models can be used in computer systems that allow people to work on complex problems using simple but powerful metaphors.

- Cognitive psychometrics. If we are to take advantage of the ability of computers to carry out complex diagnosis of student abilities and difficulties, new psychometric models based on cognitive components of school subject matters must be developed. As we discover powerful diagnostic procedures, we will be able to combine them with coaching and tutoring systems to correct the deficiencies found.

Other Research Issues

A variety of other issues must be addressed through research if we are to realize the full potential of the computer in education. Examples include:

- Motivation. Research is needed on the motivational consequences of computer-based instruction, teacher-led instruction, student group activities, and individual deskwork so that we can create a proper balance in the classroom.

- Introducing computers into education. We need to know more about social and psychological factors affecting the introduction of computers into schools.

- Computers as aids to the teacher. Explicit attention is needed to making the computer helpful to teachers, in particular as a means of increasing teacher productivity, corresponding to increased productivity in other professions. The conference report stresses the need for well designed teacher training activities.

- o Professional education of teachers. New models are needed for efficiently training teachers in computer education on a massive scale.

- o Prototype school and classroom designs. Research is needed on the best ways of organizing computer-enhanced education inside and outside the school.

- o Quality assurance and evaluation. Quality guidelines should be established for authoring systems, for instruction and assessment, for selecting software programs, for field testing and evaluating in school settings, and for developing software in the private sector. Long-term evaluations are needed of the effects and effectiveness of computer-based instruction in schools and with home computers, with special attention to the possible creation of gaps between students of different economic status.

IMPLEMENTATION OF RESEARCH

The essential basic and prototype research activities proposed here will require special stimulus and support. As incentives for private investment in research on computer applications lie in directions that promise greater economic return to the investor (e.g., office automation), Federal support for research in educational applications is essential. The talent available for the proposed work is limited, and care will be required to assure that requests for proposals attract the best available investigators.

The successful application of computers to education will require expertise in subject matter, in teaching, in computer technology, in cognitive science, and in design. It is therefore necessary to provide means for bringing individuals with these capabilities together into team efforts.

To accomplish this objective we recommend establishment of at least two research centers dedicated to applying technology and new knowledge of human cognition to improving education. The centers should have a strong resident staff and continuing involvement with teachers and schools. There should be provision for temporary appointments for visiting investigators, master teachers, and persons from the private sector, some supported by the center and some by other sources.

If these centers are established in university environments, it will make possible new graduate training programs linked to the research programs, which will prepare a very valuable new type of educational practitioner with in-depth knowledge of teaching, learning, and technology.

To ensure a healthy competition between ideas as well as good geographical access, two centers are recommended, one predominantly for research on new applications of the computer in reading and writing, and one predominantly for comparable research in mathematics and science. Each center should maintain good communication with the other and could also have some work in the other's primary area so that interactions among the areas would not be overlooked.

To assure that good ideas for research from any source can be supported, there should be an open research grants program complementing the centers.

CHAIRMEN'S REPORT

INTRODUCTION

> Nobody really needs convincing these days that the computer is an innovation of more than ordinary magnitude, a one-in-several-centuries innovation and not a one-in-a-century innovation or one of these instant revolutions that are announced every day in the papers or on television. It really is an event of major magnitude.
>
> Herbert A. Simon

New technologies alter the forms of knowledge and productivity that are important to society. The printing press led to the devaluation of humans as memorizers and to increased rewards for those who had important ideas to share. The steam engine led to the devaluation of humans as sources of mechanical power and to increased rewards for those who creatively used the new machines. The computer is now resulting in the devaluation of routine information-processing activities done by humans. However, there are great rewards for those who can creatively exploit the new information technologies.

As happened with the printing press and the steam engine, society is also being disrupted by the computer. Those who enjoyed high wages and regard because of their expertise in routine data processing tasks are being pushed aside, creating the dangers associated with a displaced middle class. Our existing educational system is under great pressure. It has not increased its productivity as other sectors of society have; educational costs have risen inordinately relative to those in other areas of the economy (in 1982, prices in general rose less than 4%, while education-related consumer costs rose 12%). We also have not succeeded in educating enough people who can adapt to technological changes. Ironically, there are many unfilled high technology jobs at a time when many people are unemployed.

Fortunately, the computer itself can help our nation out of this predicament. Just as the advent of printing created new tools for learning, so can the computer. The price of computer power is dropping rapidly. Further, the scientific underpinnings exist for the effective educational exploitation of this power. It is time to act on these potentialities. This report recommends relatively modest undertakings that can greatly increase the quality of the computer's contribution to education.

There is an important role for the Federal Government in stimulating development of quality computer resources for education. The educational computer tools that are available today fall short of what is needed. Unfortunately though, they are yielding relatively risk-free profits for those who make and sell them. On the other hand, realizing the potentials described in this report will require significant risks. Prudent business leaders will not begin taking those risks until there are demonstrations of success. Technological and educational principles must be clarified. There must be evidence that products embodying such principles are effective.

Indeed, many of the best programs now available would not have come about without earlier government research investments. Those investments were made before the possibility of inexpensive microcomputer technology was evident. They showed schools and the private sector the value of even minimal levels of expensive computer power. A similar investment is now needed to raise the nation's sights once again. The educational possibilities of plentiful computer power and improved display systems must be evaluated. In this report, a plan is proposed for refining and demonstrating basic principles for computer-enhanced education.

NEEDS AND OPPORTUNITIES

Educating For A High-Technology Future

> We appear to be raising a generation of Americans, many of whom lack the understanding and the skills to participate fully in the technological world in which they live and work.... The current and increasing shortage of citizens adequately prepared by their education to take on the tasks needed for the development of our economy, our culture, and our security is rightly called a crisis....
>
> National Science Board Commission on Precollege Education in Mathematics, Science, and Technology, 1982

A society increasingly dependent on computer power and other new information technologies will require new educational emphases. Future scientists and engineers, who will provide the knowledge and innovation needed by our industries, will need more sophisticated science and mathematics education. Many other people must be taught to build, maintain, and use the technological devices on which our society is coming to depend. All of our children need new knowledge in order to deal adequately with the products of technology in daily life, and we adults do, too. As citizens, we shall need to understand the scientific principles underlying important public decisions.

The new education we require will be quite different from w'at our schools now provide. Instead of memorizing information, students must be taught how to find it and use it. This is because the very nature of knowledge has changed. Until recently, a child or young adult, by learning a large body of facts and specific procedures, could assure a lifetime livelihood. Today, many people find that their skills and knowledge quickly become obsolete; the capabilities needed for economic productivity keep changing.

The knowledge needed to earn a living has become more abstract and symbolic. The tools of the industrial age - levers, gears, chemical reactions, and even electrical devices - could be seen and touched. Today, our world is dominated by processes that occur on less observable scales of time and size. We cannot watch the processor chip in a home computer, nor can we watch gene-spliced bacteria make insulin.

Schools have been most successful at teaching factual information and fixed procedures, such as arithmetic. In the past, they were not asked to provide universal high-level intellectual preparation. However, in a world driven by more information than can be taught, by rapidly changing knowledge, and by deeper abstractions, this is what they must now be asked to do. The well-educated future citizen will be adept at selecting information, reasoning abstractly, solving problems, and learning independently. To teach such skills effectively is a major educational challenge. Excellence in education can no longer be measured by counting the number of facts a student has memorized. Rather, the criterion must be the ability to sort through bodies of information, find what is needed, and use it to solve novel problems. We must ensure that students emerge from our schools with more than superficial understanding; they will need usable core knowledge and the ability to apply it flexibly to real situations.

This demand for changes in educational forms and content comes at a time when schools face severe economic pressures. Budgets are shrinking. Good teachers are abandoning education for higher-salaried fields, and the better students are not entering the teaching profession. We know that teachers need to learn new content and teaching methods if we are to succeed as a technological society. But, neither school systems nor teachers can afford the costs of this professional development. We know that computers can be useful in schools, but experimental innovations that have yet to be fully proven must compete for funds with light bulbs and chalk. In addition, low equipment and supply allocations (currently about 0.7% of a school district's budget) result in low incentives for educational innovation by the private sector.

Potentials for Improvement

> It appears likely, projecting trends in hardware and software technologies, that computational power equivalent to present day supercomputers will be available in a microprocessor system for under $100 by 1990.
>
> Raj Reddy

While the needs are great, the very science and technology about which we must educate teachers has the potential for making them more productive. The computer can improve education and enhance teacher productivity. It can perform routine tasks and can act as an assistant in tasks for which teachers have insufficient time. A broad range of activities in the fields of computer technology, artificial intelligence, and cognitive psychology are making microcomputer power more affordable, easier to use, and more relevant to educational needs.

The first efforts at computer-based instruction involved expensive hardware that was porly designed for children. In contrast, the quality of computer power is continually rising while costs keep dropping. The first computer used for instruction in a school cost a third of a million dollars. Current systems with good graphics cost about one thousand dollars. In addition, today's inexpensive machines are better suited to children than those once used. A child can interact with a computer by pointing to a display. Computers can control videodisc display systems. With networks, computers can themselves interact. There have been great improvements over the slow printing terminals used in the past.

Recent years have also witnessed major advances in the psychology of human information processing, artificial intelligence (the science of computer systems that exhibit understanding and problem solving skills), linguistics, and related fields. Many workers in these fields now share a common goal of understanding both the specifics and the principles of thinking, whether it is done by humans or by machines. This interdisciplinary undertaking, called cognitive science, is contributing new rigor and insights to the study of instruction.

Cognitive scientists often express their theories as computer programs. Performance of a computer program can then be matched explicitly to human performance and modified as needed. Such programs have been able to simulate many aspects of such human activities as proving geometry theorems, troubleshooting computer circuits, and solving arithmetic problems. The simulations can be used in several ways. They can be the basis for expert computer systems that actually carry out intellectual performances. They can also be used in systems that teach people. The basic approach is to combine a model of skilled performance with a program that attempts to determine which aspects of such a model are missing in a student. Strategies for teaching the missing knowledge or skill are being developed.

By exploiting new technologies and building on these new insights into human intelligence and its acquisition, it should be possible to make education much more effective and to help meet the needs discussed in the preceding section. In particular, the following major educational opportunities can be realized:

- Tutoring. The computer can be an excellent tutor. It is patient and can adapt to students' individual capabilities. Artificial intelligence methods developed in projects to build computer systems that can be expert consultants (in medicine, molecular biology, geological exploration and other areas) are being adapted for use in computer-based tutoring systems. Soon, we can expect tutoring systems to have increasingly refined teaching strategies. Tools needed to exploit those strategies are also being developed. Machine understanding of written and even spoken language is improving, along with other technologies for enhancing human-machine communications.

- Diagnosis. Computers can be used to diagnose an individual student's currently existing knowledge, thinking skills, and learning capabilities. Such diagnostic information can help teachers devise appropriate learning activities for each child. Diagnostic components will also be needed in most of the other instructional forms discussed here.

- Exploratory learning environments. Computers can be used to provide new "learning environments" which can facilitate the learning of important new concepts. In such environments, even slower students and those lacking physical dexterity can perform simulated experiments successfully, inexpensively, and without danger. Graphic animation can provide viewpoints on phenomena that are difficult or impossible to achieve in classroom demonstrations. Students can even experience simulations of events that would be physically impossible, allowing them to compare the implications of their own beliefs about the world to those of modern scientific theories. They can explore new ideas and can "learn by doing" in contexts that are tailored to their current capabilities.

- Game technologies. Computer games can provide motivation for the extensive practice that is required for facility in basic skills like reading and arithmetic. However, it is important that such games include enough diagnostic capability (see above) to assure that children who need better understanding, rather than simple practice, are also served well. Some games address issues of understanding. For example, there are a variety of business games that are really exploratory learning environments packaged in game formats.

- Networks. By connecting computers through new telecommunications technologies, it is possible to create intellectual communities without regard for participants' physical locations. For instance, students who are handicapped, have special interests, or need more intelligent colleagues could use a computer network to interact with other students like themselves. A school without a major library might still have access to a central electronic information bank. A teacher could share ideas with another teacher elsewhere who has the same problems. Resources used during the day at school could readily be shared with parents through home computers. As a result, parents could be both learning partners with their children and teaching partners with the school. Thus the home computer may become an important tool in improving adults' understanding of science, mathematics, and computer technology.

- Tools for students and teachers. Computers can be powerful intellectual tools. They can perform arithmetic calculations and are becoming able to manipulate equations; they can facilitate the writing process and expedite formatting and revision; they can retrieve information from large data bases. These capabilities can be used to shift educational emphasis from the teaching of routine skills to the teaching of the more sophisticated thinking skills needed in our technological society. They can also be used to improve learning in nontechnology areas. In fact, the French are already working on small data bases for classroom history projects.

- Helping with administrative tasks. Teachers are inundated with record-keeping chores which use time and energy that could be spent in teaching. Computers can take over many of these chores, freeing teachers to teach.

While there is a clear sense of how computers can be used, much work remains to be done. In particular, deeper understanding of the cognitive capabilities to be taught is needed. Furthermore, that understanding must be expressed in a form usable by intelligent computer systems. Simply automating the status quo will not pay off in substantial educational improvements. New ideas about effective teaching must be refined; they must be incorporated into instructional systems; and teachers need to be taught how to use them. The needed refinements can build upon recent work on human thinking and learning.

Traditional educational research focused on observable behaviors and measurable products of learning, such as correct answers to test questions. As a result, teaching efforts became more focused, and both teachers and students had a clearer sense of their progress. However, traditional theories do not tell us how to teach as much as how to determine if a student has learned. Further, test scores can be deceptive if teachers concentrate on maximizing performance on specific test items rather than teaching usable knowledge and skill. In contrast, more recent work has focused on the thought processes which underlie effective performance. Researchers have tried to discover how experts represent problem situations to themselves, how they decide on solution approaches, and how they carry out solution plans.

It is difficult to specify clearly the underlying thought processes which characterize expertise. Experts in a field are often not consciously aware of the knowledge they have and the ways in which they use it. Indeed, a major problem in teaching is that many thought processes and kinds of knowledge are so automatic in experts who teach that they fail to realize what needs to be taught.

Workers in artificial intelligence also face this problem. However, they are able to observe quickly the strengths and weaknesses of their programs and thus to uncover implicit knowledge that needs to be made explicit. Cognitive scientists now believe that the same approach can be used to uncover aspects of skill that are not adequately treated in current schooling. That is, by trying to teach a machine, they learn how better to teach humans. For example, a machine can be given all the knowledge contained in a geometry text and still be unable to prove theorems. However, by trying to build a theorem-proving machine, researchers learned that specific theorem-proving strategies also need to be taught. The same approach can be taken with a variety of cognitive skills as well as skills required on the job.

Cognitive psychology has also made progress on issues relevant to teaching methods. Of particular importance are emerging theories of cognitive skill acquisition. These modern learning theories identify stages of learning and focus on the nature of the practice required to build skill facility as well as the understanding needed to support complex thinking. Learning by doing and learning by being told both have a role in the new learning theories.

Cognitive instructional researchers are well on the way toward a richer sense of how to teach, and it is clear that the computer will be a needed adjunct for improved teaching. This is because new theories emphasize close teacher-student interactions which are inherently labor-intensive.

Underlying thought processes are best assessed and improved through techniques that build on tutorial dialogue. Practice has a revised role. More practice of skills for which the requisite underlying knowledge has been established appears to be crucial. However, teachers do not have enough time to provide frequent tutorials on a one-to-one basis or to provide fully individualized practice assignments. Fortunately, some of this work can be delegated to computer systems, if good enough systems are built.

By emphasizing advances in cognitive science, we do not mean to imply that subject-matter specialists, classroom teachers, and instructional designers cannot make substantial use of advances in computer technology without relying on improved cognitive theory. Indeed, many such advances are already being made in schools, industries, and research institutions around the country. The emphasis on cognitive science and its contributions in this report reflects our conclusion that intelligent tutoring systems are both extremely promising and less likely to become classroom realities without a coherent national effort.

REALIZING THE POTENTIAL

The possibilities described in the previous section depend upon recent developments in artificial intelligence and other areas of computer science, in the cognitive psychology of instruction, and in computer technology. However, more work is needed for these possibilities to fully realized. As discussed above, industry efforts are concentrated on low-risk efforts that generally fall far short of the potential that is evident for computer systems that take advantage of recent scientific advances. To attract serious efforts from the private sector, two things are needed. First, school leaders need to know more about the kinds of computer tools for education that will soon be possible, so that they will demand more of instructional computer systems. Second, a number of specific research issues need to be resolved so that private developers see artificial intelligence and cognitive instructional psychology as sources of principles for product development. The basic conclusion of this conference is that striking improvement in the quality and productivity of instructional computer systems is attainable with a coherent and sustained research investment.

This research should set new sights and provide new options for local school systems. The conference asks the Federal Government to take some of the initial risks and to set the stage for excellence in computer-based education.

We recommend that the Federal Government fund a coherent effort to build exploratory prototypes of the intelligent instructional systems we believe are possible. Such prototypes can act as guides for private industry and also as classroom-based laboratories for needed basic research. They would provide a vision of the range of possibilities for the computer in education, forcing attention to the research issues needed to achieve those possibilities, and helping us to solve the problems involved in bringing new sources of learning power into the nation's many and varied school systems. They would also be a medium for more relevant basic research on the specific processes involved in skilled reading, writing, mathematics, and other intellectual performances, on new ways to adapt to individual differences in aptitudes and progress in learning, and on the applied psychology of student and teacher interaction with automated instructional systems.

Research undertaken to exploit the educational applications of computers can also help guard against some potential dangers. In particular, it can help avoid the discrediting of promising ideas by poor implementations, the wasting of limited resources on projects with poor prospects, and the use of good technologies in harmful ways. Education in the computer age must not cause students to be isolated from each other by electronics, bored or confused by poorly designed software, or rendered passive by systems which do not promote exploration or initiative.

The next few sections summarize the general recommendations of the conference for (1) a coherent, continuing effort; (2) prototype research; (3) targeted basic research; (4) some related concerns; and (5) issues of implementation. More detail is provided in the conference proceedings which are printed in a second volume.

A Strong National Effort

In order to be productive, the proposed projects should be integrated into coherent combinations of basic, prototype, and field research. Some of the researchers who lay the foundations for improved uses of computers in the learning process must be involved in field testing so that research and practice can inform each other. Researcher interactions with teachers as they learn to use these new tools are especially important. Prototype teacher training efforts are a partial responsibility of some of the researchers who are funded based on the recommendations of this conference. At the very least, researchers should be major consultants in the design of training systems, both to preserve the involvement of the knowledge producer in knowledge application and because of the feedback that teachers can provide.

The appropriate role of government is to stimulate these new technologies, after which private enterprise can more efficiently realize the bulk of their applications. This suggests that researchers must be concerned not only with how their ideas will work in real schools with teachers and students but also with the practicality of their proposals.

Projects should be large enough in scope and duration to provide clear outcomes. While there will be need for both large and small projects, the more exciting possibilities discussed in this report cannot be realized, even in prototype form sufficient for testing of efficacy, without multi-year efforts. Interdisciplinary groups of cognitive instructional researchers, computer scientists, graphic experts, teachers, other subject-matter experts, school administrators, and parents will be needed. The best experts must be attracted to this effort. The work need not be restricted to a single institution; indeed that could be a serious limitation. However, it should be concentrated mostly in projects which use exploratory prototype systems as laboratories for basic research and studies of school implementation mechanisms.

Prototype Research

Successful education depends upon complex interactions of many people. Because of this, it is impossible to know just how theoretical ideas developed in the laboratory will work out in practice. Once a science has generated an instructional principle, it must be tested and refined by using it. The substantial promise in computer technology and the cognitive sciences comes largely from laboratory research and from technologies that have yet to be fully exploited in classrooms. The next step is prototype research, in which the basic principles are refined by trying them out in pilot applications.

To be useful, prototype research must be carried out to reflect and test explicit theoretical ideas about instruction. This will allow us to discover why proposed methods work (or why they do not) and to lay the groundwork for further scientific inquiry. At the same time, practical evaluation of those methods can be started.

Prototype projects must be of high quality, setting new standards for excellence and not discrediting good ideas with poor implementations. It is preferable to have a smaller number of high-quality prototype projects, carried out by the most talented scientists, designers, and technicians, than to have a larger number of lesser quality.

Prototype research should allow teachers, administrators, and students to contribute their own ideas to the work. A recent example of how this can be done is the prototype project to place powerful computer database resources on the USS Carl Vinson. By heavily involving the prospective captain and his officer team in the development of this project, the research team has been able to discover strengths and weaknesses of the system m[illegible] more quickly. More important, the system has become much more powerful than the researchers originally intended. The captain has added other software on his own initiative. He commissioned an intelligent expert system to help manage flight operations as well as an instructional system that uses some of the database capabilities the researchers wanted to test. These additions came about because they were evident to the captain as sensible possibilities once he became a knowledgeable partner in the project. It is unlikely that he or his superiors would have agreed to let the researchers go as far on their own. The captain used his own budget for these additions, which probably avoided conflicts over whether the original effort could be stretched to accommodate both scientists' and officers' new ideas.

This suggests a model for prototype research on computers in education. A project should be conceived as a partnership among researchers; a teacher, school, or school system; and in some cases, private companies. The ground rules should be that the general research goals proposed to the government will be met, but that refinements and additions to those goals will be encouraged. Separate funding (not part of the original Federal contribution) may be needed for these refinements, from local private and public sources.

There should be substantial freedom for researchers to propose their own ideas, and some may propose worthwhile smaller-scale efforts. However, there are several prototype projects that seem particularly important, and we discuss them below.

Coaches And Tutors

Artificial intelligence research has already resulted in several preliminary versions of a computer tutor. These systems have expert knowledge about a subject matter, can diagnose the level of a student's knowledge, and have strategies for tutoring the student to higher levels of understanding and skill. One system can improve students' play in a game that requires construction of arithmetic expressions; another coaches troubleshooting of an electronic circuit; a third provides help in infectious disease diagnosis. It is time to explore what such a system must be like if it is to be useful in a school environment.

Given national problems in the level of science and mathematics skills, an obvious choice for a tutorial domain is mathematical or scientific problem solving. The conference encouraged projects that explore, via pilot system building and testing, computer-based tutoring in the solving of algebraic word problems, development of computer algorithms, solving of physics and chemistry problems, and similar tasks.

Another possibility is a writing coach to aid students as they try to generate ideas and plan their writing. It could also help students think about their goals and encourage them to continue writing. When the student has finished a draft, an intelligent text analysis tool could comment on spelling, grammar, and style, and make suggestions for revision.

Diagnosis

Given an adequate analysis of human cognitive processes, computers can be programmed to ascertain quickly a student's existing knowledge, understanding, and misconceptions. Computer diagnosticians would make teachers more aware of the ways in which procedural skill and conceptual knowledge combine to produce good performance. They could show them which components are deficient in any particular student and help them become aware of areas in which all of their students need further work. Better tools for diagnosis, properly used, can help raise the goals of education from the finishing of textbooks and passing of tests to the achievement of powerful intellectual skills that can be applied in real-world settings. Further prototype research on diagnosis should be encouraged.

<u>An example of computer-based diagnosis.</u> Our enthusiasm for the possibilities of computer-based diagnosis is supported by a project, called BUGGY, that John Seely Brown, Richard Burton, and their associates have developed in the last few years. They built a diagnostic system that could determine

whether deleting one or two specific steps in the subtraction process would lead to the exact error pattern a child displayed. For about a third of the children studied, a specfic knowledge deficiency was detected that could account for the child's problems. Experienced teachers often cannot detect these weaknesses and end up dealing with errors merely by assigning more exercises. This practice on doing arithmetic incorrectly does not help. With computer programs such as the one already developed, specific conceptual problems can more readily be identified and overcome.

The initial laboratory approach required the full power of a half-million--dollar computer to analyze children's answers to a set of subtraction problems. The diagnosis program has now been reduced to fit onto microcomputers that many schools already own. It is possible not only to detect missing knowledge in arithmetic but also to provide hints that lead students to discover missing steps in their arithmetic procedures.

Learning Environments (Simulated Laboratories and Games)

The computer can be used to simulate, through animated displays, a variety of phenomena from which students can learn. These include both the laboratory exercises already in use as well as activities that would be impossible to conduct with real materials. There are a number of advantages to such simulations. They may be cheaper, since no special equipment beyond the computer system itself is required for any given simulation. They can operate on different time scales, allowing exploration of processes that occur too quickly in real life or that take so long as to be incompatible with the pace of schooling. Similarly, size is no barrier; it is as easy to simulate events inside a molecule or events involving an entire galaxy as it is to simulate something that one could see out the classroom window. Simulated events do no physical harm, while many important laboratory demonstrations can be dangerous. Most important of all, simulated phenomena can be presented in a way that allows students to focus on centrally important events without being distracted by logistic details. Even when not a complete substitute for real laboratory work, simulated demonstrations can be a good preparation for the real thing.

Simulated laboratories allow exploration of hypothetical or fictitious situations that may be absent, or even impossible, in real life. For example, a simulated laboratory might allow students to understand more specifically how their ideas fail to match our understanding of the world.

Simulated laboratory systems are ideal prototype research facilities for refining our ideas about the importance of learning by doing. Properly designed, they can allow students to formulate hypotheses, test them, analyze results, and refine their conceptions. Moreover, they can provide the student with a record of the course of his or her investigations, permitting greater self-awareness of thinking and learning.

Game formats. Some of the simulation work should involve game formats as well as pure exploratory and tutorial modes. Experimentation with several different instructional modes based upon the same underlying simulation capabilities will permit controlled studies of the different ways in which each mode can be effective.

Integrating computer-based exploratory environments and tutoring systems. A number of good simulated laboratories have started to appear on the market. For example, students can predict the outcomes of chemistry experiments and then see the experiments simulated. They can conduct simulated multigeneration breeding experiments on birds and fruitflies. They can even experience what flying a plane is like. The area where research is needed is at the edge of such systems, figuring out how best to incorporate them into successful instruction. For example, recent research findings indicate that many students, even after taking a physics course, do not understand the basic mechanical principles that interrelate force, mass, and acceleration. Their knowledge of the physical world is stuck at the level of Aristotle while they live in the world of Newton and Einstein. In a physics laboratory, students can be shown the effects of forces on objects, but they misperceive those effects. Now, computer programs are available that allow students to compare what would happen if their naive beliefs were true with what happens in a world governed by Newton's Laws. After all, things can happen in a video display that might be impossible for real physical objects. The implicit message for the student is, "If your beliefs were true, then this is what would happen, but in fact here is what happens instead." However, that message needs to be made explicit, and we need to know more about what students actually take away from such simulations. One way to do this is to build an interactive tutoring system which could engage in a conversation with a student, using the simulations as a tool for discussion. Such tutors are achievable within a few years. They could be very useful in helping researchers discover how simulations can be used effectively. They could also be used to upgrade the knowledge of science teachers.

Computers As Tools For Students

Computers can be powerful intellectual tools and media of expression for students. With the aid of methods of artificial intelligence, they can even be genuinely intelligent assistants. For example, computers can do arithmetic calculations, manipulate algebraic equations, and construct and transform graphs. They can facilitate writing and revision by allowing easy storage and manipulation of text and can correct spelling and suggest improvements in grammar. They can also be powerful visual aids to design activities. However, just as we once wondered whether calculators were good or bad for children, we now have concerns about these new tools. Through prototype research programs, we can begin to learn how they can improve learning and which ought to be made widely available.

Automated dictionaries and interactive text. The conference noted that the microcomputer and videodisc technologies can be used to produce an automated dictionary and thesaurus. With such a system, definitions of words can be accessed while reading, through touching the screen, or while writing, by typing an approximate spelling. Preliminary dictionary programs designed for today's classroom microcomputers are already available, at low cost.

There is some evidence that children who do not learn very well are less prone to attend to precise meaning and to detail of a text. By decreasing the effort required to access information about terms used in texts, it may well be possible to create a situation in which slower learners learn that precision and completeness in reading a text will result in better learning. Prototype research exploring such possibilities could be combined with the more basic research on thought and learning processes mentioned below.

Similar benefits may come from extending the automated dictionary concept even further, into the interactive text. The prototype conferees had in mind would include the kinds of explanatory resources just described, so students could ask to have a concept explained or a point elaborated. In addition, recent work on individual differences in learning skills suggests that the interactive text should have questions embedded within it for students to answer. Analysis of a student's answers to those questions would allow subsequent presentations to be geared to his or her level of understanding.

Electronic libraries and data bases. A variety of computer-accessible data sources have recently become available. These systems might be important forces in improving education. They could allow students to access much richer and more recent information than is present in most school libraries. Computer-accessible databases can serve as source material for student research and writing projects. When computational aids are also available, students can access real quantitative data and learn to use it. Working with information about a real space-shuttle launch, for example, is likely to be both more motivating and more informative than working with unrealistically simplified fictitious data. In addition, the skills of data base access and information retrieval are themselves part of what will constitute literacy in the future. Indeed, literacy has always consisted largely of sorting through existing bodies of knowledge, putting ideas together in new and productive ways, and learning how to learn. Students can best learn literacy skills in the context of substantive information needs and rich information resources.

Computers As Tools For Educators

Feedback, grading, and other teacher aids. There are already commercial tools available for increasing teacher and administrator productivity by facilitating record keeping, grading, homework assignments, and lesson planning. Some of the approaches need considerable refinement, but this is likely to occur without further Federal investment. A more sensible area for new activity is on tools for instruction in writing, another problem area in U.S. education. Many students already write their essays on word processing systems, and this can be expected to become even more prevalent. Once a student's work is in machine-readable form, it becomes possible to provide new types of essay-correcting tools to teachers. One possibility is a system for efficient teacher commenting on students' writing projects. In addition, spelling and grammar correction and text summarization systems would help save teacher time. It is important to explore the effectiveness of such approaches in order to ascertain the potential of integrated computer systems for schools.

Software authoring and customizing systems. No national organization, whether government or publisher, can decide what is best for all students in all schools. Therefore, it is essential that teachers be able to modify instuctional software systems to suit the needs of their students and the community they serve. One step toward this end is the development of software authoring languages that teachers can use to adapt software to their specific needs. It is too early to specify a complete authoring environment for teachers, but it is time to start exploring the uses teachers make of tools that allow them to customize software for their specific needs. One or two of the proposed prototype systems should include specific resources that allow teachers to make modifications.

Communication Networks

Networks, videotex facilities, data banks for parents and children, and computer-based bulletin boards are already starting to be developed. Such networks can enable interactions between students with similar interests or similar special needs (e.g., the handicapped and the gifted). They can also allow access to information and tools not available in the classroom. Finally, they can be a basis for teachers' exchange of resources and ideas and for interactions between teachers and the developers of new educational programs or methods. Attention must be given to richer analyses, including observational analyses of usage, cognitive analyses of the skills required to use network resources, and assessment of the contributions of such resources to the development of reading and writing skills.

Computers In Teacher Education

Some of the prototype projects to be funded should also examine the role of computers in instructing teachers about the potentialities and limitations of computers, so they can cope adequately with the computers they encounter in their schools and achieve a level of "computer literacy" at least on a par with their students. Teachers also need to learn more about recently-demonstrated instructional principles and teaching techniques, and they need to develop new educational goals for preparing students to live in a technologically driven society.

These teacher (re)training needs might themselves be addressed with instructional computer systems. This would itself be a form of learning by doing, since teachers would be using computers for their own learning in ways similar to those used to teach their students. Thus, prototype research on computer-based teacher training is an important part of the overall research agenda.

Basic Cognitive Research

If we are to realize the potential of computer technology for helping students achieve high levels of capability in mathematics, science, reading, and writing, targeted basic research of several kinds will be needed. Cognitive research should build upon advances in the psychology of complex human thought processes and in artificial intelligence. Intelligent tutoring systems cannot be built without first analyzing the specific knowledge they are to help students learn. Research is also needed on how such knowledge analyses can be turned into effective instructional strategies. The necessary research on the nature of skill and the nature of learning is well underway, but continued work is needed. Prototype research projects can shape that work into more practical directions.

Certain types of computer science research are also needed. This includes research that explores the uses of computer technology in diagnosing individual student's difficulties in learning basic skills, acquiring new knowledge, and solving problems. In addition, existing work on computer-based intelligent tutors must be refined by testing results in the course of the prototype projects discussed above.

In addition, we need to understand what motivates students to become active readers, writers, and problem solvers, and how computers can be used to support these interests and not limit them. Researchers must remain alert to the effects, both desirable and undesirable, that various uses of computers may have on students' patterns of development and on the social organization of the classroom.

The conference participants support long-range national investment into general basic research in all these areas. However, we limit our recommendations here to specific activities from which we expect a shorter-term payoff: enhanced design principles for instructional uses of computers in education. We also strongly urge that the research integrate the insights of teachers and other education practitioners with those of scientists. The development of useful systems will rest on the twin pillars of practical and theoretical knowledge.

Thought And Learning Processes

It is important to obtain a better understanding of the thinking processes that are needed for acquiring sophisticated concepts and for solving problems. Mathematics, science, and writing are all problem-solving activities, and the computer appears to be well suited to coaching students through problem solution. All basic schooling goals involve deeper understanding and the ability to acquire new knowledge autonomously. Thus, the skills of learning and of problem solving in school subject matters should be a specific focus of research.

Expert and novice thinking. Recent studies have revealed that students approach learning tasks with many prior conceptions, based on life experiences, which can be obstacles to new learning. These conceptions are very resistant to change. Work to date has been descriptive. Future work should be increasingly analytic, aiming to understand why students' conceptions persevere so strongly, how they might be modified, and how the conceptual difficulties students will have when they encounter new subject matters might be predicted.

Work is also needed on high levels of competence. Studies designed to make explicit the unconscious knowledge that enables expertise will be important both in identifying more specific curricular goals and in developing ways to achieve them. Assuming that current educational practices are not yet perfect, such studies might even go beyond existing expertise, devising new strategies for thinking that are better adapted to students' limited capabilities. Just as word processing tools and spread-sheet analysis programs have increased the effectiveness of businesses, there may be similar tools for increasing learning capabilities. Better understanding of the components of high levels of expertise can inform efforts to build such tools.

Until recently, theories of learning dealt only with very simple learning tasks. However, new insights into human thought processes are leading to the development of improved theoretical models that can account for the acquisition of more complex knowledge and skill. As we shift our sights from basic, primary skills to intellectually demanding activities such as science, mathematics, and computer technology, these new models will be especially important. Principled approaches to instructional design should produce more effective and efficient learning.

Comprehension and writing strategies. Research to date suggests that even secondary school students have difficulty summarizing texts, defining main points, skimming text to abstract information quickly, taking notes, and planning and revising compositions. Conference participants envision computer aids that will help students develop these higher-level skills. However, greater understanding of the cognitive components of these skills is needed before we will know which possibilities are likely to pay off. Even after the strategies most effective for various reading and writing tasks are identified, there is still the problem of discovering effective ways to teach those strategies. We also need to assure that the automated tools that are provided for students do not become barriers to better human skills.

Using the computer to stimulate autonomous cognitive facility. Specific research is needed to promote the design of effective computer programs for assisting, prompting, and teaching effective comprehension, writing, and problem-solving skills. We need to know how reasoning coached by a computer mentor becomes internalized so that students learn to reason actively, not to wait for the machine to do the thinking. We need to know when (and for how long) students should be actively coached through intellectual tasks. The successful use of coaching techniques will depend on the materials and context in which they are applied. We need to know more about the conditions of prior knowledge most conducive to internalization of planning and reasoning procedures and the conditions that will best foster learning of new content in diverse subject areas. We also need to know which mentor functions are best carried out in the social milieu of the classroom and which in the more private space of the computer terminal.

Knowledge Structure And Knowledge Retrieval

New knowledge is accumulating at an accelerating rate. In spite of our optimism about improvements in how we teach, work will also be needed on what to teach. Recent work in cognitive science indicates that the manner in which knowledge is structured can greatly affect the ease with which it can be used in various intellectual tasks. Further efforts are needed to learn how the form in which knowledge is represented can facilitate its later recall when needed to solve a problem and its generalization as more experience and new knowledge is acquired. It is especially important to identify core knowledge which can allow derivation or subsumption of large amounts of related information. We need to understand the processes involved in working from core knowledge, and we need to know whether the specific core requirements might differ for students with different aptitudes or different occupational expectations.

In addition to better understanding of what students need to know, further research is needed on the cognitive skills they use to retrieve that knowledge when they need it. We need greater knowledge about how humans (young and old) store, process, and retrieve information already contained in their heads and how they can improve the efficiency and effectiveness of these processes. We need to understand the role that self-awareness and self-management strategies play in both the learning and the retrieval of knowledge of different forms. If computer-based instructional systems and information resources are to be effective, we need to know how information sources (documents and computer files, electronic and traditional libraries, printed and electronic dictionaries) can be designed to facilitate information acquisition by humans.

Mental Models

"Mental models" are relatively simple conceptual schemes used by people to explain, predict, and control phenomena they encounter. For example, the "spread sheet" is a mental model that many business people use to facilitate the handling of financial data and the preparation of reports. Even though computers do not need spread sheets to do the work for which people once used them, the spread sheet has been retained to facilitate human-machine communication. Mental models may be scientifically or technically primitive, but they allow people to gain control over forces in their environment, such as automobiles, computers, and complex business data.

It is important to study the mental models people use for various intellectual tasks, since such models allow computers and people to work together on complex problems using simple, but powerful, metaphors. This should especially be the case when a scientific or technical domain is being taught to students with less well-developed scientific capabilities or interests. Different models can be formulated to deal with the same phenomenon or device. For example, a computer scientist's mental model of a computer might be different from that of a computer repair technician or a business person using one for word processing. We need to understand better the principles that might account for the success or failure of mental models.

Diagnosis of Cognitive Capabilities

A cognitive psychometrics. As the complexity of diagnostic assessment increases, new psychometric models based on cognitive theories of competence in school subject matters must be developed. These models will be needed to guide decisions about how to improve, automate, and optimize diagnostic testing. They will also help us summarize and interpret complicated patterns of errors in students' writing and problem-solving performance. Further, they will permit us to study and summarize changes in students' diagnostic profiles over time.

As powerful ways to diagnose students' abilities and difficulties are discovered, it will become possible to combine diagnostic assessment with coaching and tutoring approaches. Diagnostic assessment and training of basic skills by interactive computers may be important for overcoming the educational difficulties of students from special populations, such as the handicapped, the learning disabled, and those from environments with differing language experiences or differing exposure to modern technologies.

A cognitive psychometrics will also facilitate better evaluations of computer-based instructional tools. The questions to be asked of such tools include whether they have any positive effects at all; how long those effects endure; whether they transfer to everyday situations; and whether they replicate over different student populations, materials, and environments. To answer these questions, both conventional and new approaches will be needed, but the new approaches based on cognitive theories of competence are particularly important. They may provide knowledge which can help shape better principles of instructional design, principles grounded in a rich understanding of the thinking processes that we want our children to acquire.

Artificial Intelligence

Although artificial intelligence is primarily concerned with computers, some of the research in that field is highly germane to educational applications. Because efforts to make computers behave intelligently require a great deal of explicitness, they can yield insights about human thought processes. Also, artificial intelligence research efforts to make computers more usable by people without specialized training will have application to the design of computer-based instructional systems, especially intelligent tutors and diagnostic devices. The research the conference envisions should involve a number of scientists with backgrounds in artificial intelligence.

Other Research Issues

Motivation Research

Students' use of computers in classrooms may affect their motivation to learn in both desirable and undesirable ways. The availability of powerful computing resources to help students acquire basic skills may enhance development of a personal sense of intellectual competence, leading the student to participate more fully and effectively in everyday classroom activities. There also may be negative motivational consequences arising from misuse of computerized tools in the classroom. Excessive interest in computerized learning games as a means of entertainment may lead students to lose interest in participating in teacher-led activities or sustained independent work. Students who are already poorly accommodated to the social life of classrooms may become even more poorly adjusted if they interact less with other students and teachers and more with computers.

Research is needed on the motivational consequences of instruction by computer, teacher-led instruction, student group activities, and individual seatwork. We need to know which approaches should be used when. We also need to understand the motivational consequences of different kinds of computer-based learning. If less able students use computers primarily for diagnostic and remediation purposes while more able students are engaged more creatively, will only the latter come to regard the computer as a powerful tool rather than a taskmaster? We also need to better understand game environments, so that we do not fall in to the trap of motivating children to focus their attention on superficial reinforcers while playing "educational" games.

Research On Introduction Of Computers To Education

Some research is needed on social and psychological factors involved in introducing new educational technologies into existing social systems like the school. Studies are needed to identify factors that lead people or institutions to resist or accept new innovations. This knowledge can help in devising improved methods of communication and participation that might facilitate change and increase the effectiveness of innovations. We need specific knowledge of the perceptions of teachers, students, parents, and school administrators when different forms of technological innovation are introduced. An important component in this research must be consideration of the costs involved. We need to know both the monetary and social costs attached to different potential improvements and the effects of such costs on acceptance. Some of this work can be carried out in the context of the proposed prototype efforts if the projects are of sufficiently long duration.

Research is needed on new roles for teachers, new organizations for classrooms, and new educational settings. For instance, analyses should be concerned with (a) the role of the teacher as selector of existing courseware, as courseware developer, as classroom manager, as coordinator of "intellectual communities" established through computer networks, and as creative tutor and coach; (b) the role of the student as peer tutor, network "community" member, database user, courseware developer, author, and editor; and (c) the role of the administrator as the person responsible for learning resources and computer courseware development centers, as a teacher training specialist, as network library coordinator, and as research and development liaison coordinator.

Helping Schools Become Communities Of Educational Computer Users

Even the best tools for computer-based education will not be widely used unless (a) care is taken to put them in forms that solve school systems' problems; and (b) effort is allocated to teaching teachers how to use these resources. In this section, a set of goals and concerns are outlined that conference participants felt should pervade all national efforts to improve computer-based education.

Computer as helper, not master. The computer can be our servant in education, a new kind of servant that can be asked to do things we have never before tried to do ourselves. We must be trained in order to best be served by it. In our vision of new possibilities, we must also recognize the limitations of our computer helper. A computer cannot replace human role models in education, nor is it smart enough to supplant human teachers in their sympathetic interaction with children. Our national goal for the computer in education should be to find ways for it to help children learn, help eliminate teacher tedium, and give the teacher effective support systems beyond the capacity of parents, local schools, and school districts. Computer enhancement of teacher productivity offers a way out of the dilemma of rising education costs leading to lagging teacher salaries and thus to the loss of many of our most competent teachers to other professions.

Need for training. Our experience with the introduction of educational television suggests that schools and school districts must plan for staff training if new technologies are to be fruitful in the classroom. In addition to subject-matter revitalization, as has been provided by such resources as NSF Summer Institutes and the National Writing Workshops, there will need to be opportunities for teachers to become familiar with computer resources and to learn how to use them well. Excellence in the technology-driven education world we are entering will require the development and evaluation of innovative prototypes for training present and future school personnel. Obviously, some of this training might itself be delivered by computer, and this is a matter some of the prototype research efforts should explore.

While the need for training programs is beyond the purview of this conference, the conference felt compelled to respond to teachers who pointed out the lack of systematic concern for training in computer-related educational approaches, especially for teachers of subject matters other than science and mathematics. Teachers are underpaid and underequipped; they cannot be expected to learn about computers on their own time and with their own resources. The conference recommends that issues of teacher (re)training be the subject of a planning effort similar to the one we have undertaken.

Prototype school and classroom designs. Research should be supported that leads to well-motivated prototype designs for computerized learning facilities: computers in classrooms, combinations of in-school and out-of-school facilities, and, if it should prove effective, resource center arrangements. Demonstration sites that can be evaluated will be necessary. Such sites should emphasize joint involvement of students, teachers, and parents in the learning process. Again, they should address the issue of *when* computer-based activities are effective, not just *whether* they are.

prototypes that provide students and teachers with free and rich access to the computer throughout the day are especially important.

Quality assurance. The software initially sold to school systems was mostly of mediocre quality or worse. A variety of initiatives will be required if this situation is to improve to the point where we can think of computers in the schools as a major factor in fostering excellence in education. Efforts should be made to integrate practitioners, scholars, technical experts, computer companies, and publishers into the computer system development process. Work is needed on systems for field testing and evaluating all courseware, not just prototypes. Quality guidelines should be established for authoring systems, for instruction and assessment, for selecting software programs, for field testing and evaluating in school settings, and for developing software in the private sector.

Telling teachers and parents about uses for the computer in education. Teachers and parents need to now what kinds of effective uses of computers are currently possible. The task of reporting results from the proposed research must involve the researchers themselves. This is because the ideas from cognitive and computer science that support this work are very new. Consequently, they are easily distorted as people try to fit them into their existing ways of thinking about the world. Scientists supported in the proposed research activities bear particular responsibility for explaining their results to parents and teachers or at least for monitoring the explanations produced by others.

In addition, a research center or a larger research contractor involved in other proposed projects should have the charge of producing information on computer usage for the schools. A series of reports should be prepared that are easy for parents and teachers to understand and apply. The series should include reports of research results and their implications for excellence in education, critical guides to available computer resources, and models of effective computer deployments and usage with different levels of computer resources. Reports should include accounts of successful activities generated at the local level and perhaps also analyses of why those innovations were successful and how they can be replicated.

Long-term evaluation. The conference also recommends long-term ongoing evaluation of computer uses in schools to assess the effects of individualized computer-based instruction on the achievement and self-concept of students. Studies should be conducted to compare computer-based instruction to alternative approaches. Other assessments should review the effects of hardware and software on such student variables as achievement, time-on-task, self-concept, and motivation, and on such teacher variables as effectiveness and burnout. A broad study of the impact of computer and video technologies on children's development should be considered.

Challenge of new technology in a democracy. Some people fear that the computer will increase the already wide gap between the haves and have-nots, between those who use computers routinely in their homes, and those who cannot afford such luxuries. If this tool is to be made available in our schools, it should be made available to all children equally. A unique opportunity of the new technology for education is to extend the learning environment beyond the school and the home. Yet, special care must be taken to avoid intrusion on parents' rights and responsibilities and to assure that equality of computer-related opportunities in the school is not eroded by differences in home computer availability.

A community of learning beyond the classroom. Part of the work of learning, even school learning, is done outside of school. Students are given homework for a variety of reasons. It offers a chance to reflect on problems outside the regimented time schedule of the fifty-minute hour. It provides the additional practice that can be done largely without teacher assistance (or at least is not the highest-priority use of teacher time). If the computer-based learning environment moves beyond the walls of the school, homework can change substantially. Groups of students can work together even if they live in different parts of town. The work of learning can occur at home as well as at school and in ways that go beyond homework as we currently know it. Parents can be active participants in this extended learning process as well.

However, a community of learners can exist only if its participants have become socialized in the ways of interaction. Parents need both specific training in network information access and, more generally, a chance to keep up with their children. Our society depends upon a respect for the wisdom of age that will be seriously eroded if the computer revolution leaves parents and teachers behind.

Economic realities. The visions we have presented must be mediated by the realities of a world in which providing pencils to students is a burden some teachers meet out of pocket and in which the costs for home and school machines will compete with demands for teacher salary improvement and tax reductions. The value of a higher capital investment in computers for education must be demonstrated with care in exemplary prototype projects which are visible, criticizable and assessable.

Implementation Of Research

The proposed basic and prototype research activities are essential to the successful realization of the potential of computer and cognitive technologies for education. However, fruitful implementation of this research will not be easy. The fundamental difficulty is that while progress in computer and other information technologies has been very rapid, systematic efforts to apply these technologies to education are in their infancy. All incentives for talented researchers and for private investment lie in directions with better economic support: office automation, integrated circuit design, and even arcade game production. Public schools are presently beset by financial difficulties, as are universities. Both hear most clearly the demands from traditional cost centers.

Many school systems and many university researchers will respond to any call for proposals to do the work that is needed. However, few will have the specific talents needed to pursue the work that must be done. If the

Federal goal is to realize the full potential of computers in schools, great care will be needed to assure that requests for proposals attract the best available computer experts, cognitive scientists, and educational specialists.

Forms of projects. The talent available for the proposed work is limited. At the present stage of knowledge, it would be unwise to focus all efforts in one or two directions which might perhaps not turn out to be productive. Conversely, it would be unwise to undertake so many diverse efforts that talent and funds are dissipated in activities too small to be significant. This suggests a combination of large and small projects. In general, projects should be funded for periods long enough to assure not only scientific advances but also the translation of those advances into useful principles of instruction.

Successful applications of computers to education will require many different kinds of expertise, in subject matter, in computer technology, in cognitive-science areas, in teaching and in design. It is unreasonable to expect that all these capabilities will be possessed by a single individual. Hence it becomes important to provide contexts where persons with different kinds of expertise can effectively collaborate as a team. This collaboration cannot be casual. Rather, each expert must know or learn a substantial amount about the other relevant fields so that teams can operate effectively.

Because of this need for collaborative activity, the conference recommended the establishment of some research centers dedicated to the advancement of new scientific and technological approaches to education. These centers should be widely accessible to educational researchers and designers throughout the nation. Like the Fermi Laboratory, they should both produce research directly, through a core staff, and provide resources for others to do work that requires special resources.

These centers should have a good resident staff doing work of high quality. To attract such people, firm, multiyear commitments will be needed. In addition, the centers should provide a working environment which talented researchers and designers from other places could use for more limited periods. Such visitors would ensure intellectual vitality by providing an influx of new ideas and they would help in disseminating the ideas produced in the central facilities. Some of these workers might be supported by the centers while others would use grant funding or other sources. Limited resources should be provided for continuation of work initiated by a visitor even after he or she leaves. This might be an ideal training vehicle for graduate students. With adequate computer networking, it is quite feasible for a researcher to bring a student to a center, start a project, and have the student stay to finish it, reporting to the senior researcher by network.

Master teachers should be recruited for temporary visits to the centers. They could provide realistic inputs to the design of new instructional prototypes while there and would return to their schools with new approaches which they could pass on to their colleagues. Funding for such visitors should be included in the research center plans.

In order to ensure a healthy competition between ideas and to provide good access, there should be at least two such centers. A single facility would run the risk of being unduly fixated on a single educational approach and might suppress alternative points of view. It would also be geographically less accessible to parts of the country. One center might have a stronger mathematics and science orientation, while the other might be more strongly oriented in the direction of language skills. Given the present status of the disciplines which must contribute to the efforts we propose, some overlap of subject matters treated in the two centers is inevitable and desirable.

In addition to the research center program, there should be a complementary open research grants program for individual investigators.

General basic research programs. We end by reiterating assertions that the potential breakthroughs in instruction we have been discussing are largely the result of capital investments by this country in basic scientific research over several decades. As we begin exploiting the products of this investment, it is important to remember our obligation to the next generation. Conference participants strongly encouraged the funding of less targeted basic scientific research, including cognitive and social research, at adequate levels. Just as the present opportunities are the result both of making the necessary investments in the past and of trusting in part of the judgements of the scientific community in deciding where to invest, so do we envision that future opportunities will depend upon a significant and predictable investment allotted by the best experts that can be found.

CONFERENCE PROCEEDINGS

THE COMPUTER AGE

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The title of this conference was chosen with either a good deal of care or a good deal of luck--I think care. It is a conference on research, on computers, and on education, which leaves us a good deal of leeway in finding out what are the useful and profitable ways of putting computers to work in education. And, of course, the phrase "research on computers" is itself somewhat ambiguous. It could mean research about computers in education. But it might mean research in which you do your research on computers. I will have something to say about that in the course of my remarks.

The Computer Revolution

Nobody really needs convincing these days that the computer is an innovation of more than ordinary magnitude, a one-in-several-centuries innovation and not a one-in-a-century innovation or a one-in-ten-years innovation or one of those instant revolutions that are announced every day in the papers or on television. It is an event of major magnitude. Every major innovation goes through a longer or shorter period that might be called its "horseless carriage" phase. Just as the automobile when it was introduced was simply another way of pulling a cart along the road, so with every really novel innovation our first thought is that it is simply going to do something we have been doing all along but do it better or cheaper or faster or more conveniently.

We are always surprised when these innovations turn out to have a significance for us that is quite different from the technology we thought we were improving. So the real significance of the automobile for us has not been cartage, although an awful lot of things are hauled over the roads these days. If we weren't hauling them over the roads, we would be hauling them over the railroads, which would make the railroads feel a lot happier. But it wouldn't be any great thing, a few percent one way or another in the efficiency of our economy. The importance of the automobile was its creation of the suburbs, and was its creation of the 2,000 mile vacation, complete with children and dog. Those were the real significances of the automobile.

And similarly, with the computer. Of course, the computer age is a much newer age than the automobile age, and we have not really found out yet what lies beyond the horseless carriage phase. Here the horseless carriage phase means the number-crunching phase. Computers were, of course, invented to be number-crunchers, although some of their inventors, like Babbage, a century ago, or Allen Turing in this century, had the foresight to see that they were really very much more than that.

Nevertheless, after 25 or 30 years of extensive use of computers in the world and in this country, 95 percent of the computer power and 95 percent of the computer time is still being devoted to crunching numbers either for purposes of scientific and engineering calculation, or to keep the payroll and keep the ledgers in business organizations.

Perhaps the most urgent target on our agenda when we talk about research on computers, whether in education or in any other field, is to devote our research efforts to finding out what lies beyond that number-crunching, what computers really are about, what their potential really is. Now, events of the past three to five years--with the micro-computer suddenly arriving in the household (partly as a result of miniaturization and cost reductions) and the computer coming to work in the business place and the home as a word processor--all of these things have made us much better prepared than we were even three to five years ago to understand that the computer revolution has very little or nothing to do with arithmetic.

Well, that is not quite right, is it? Computers are going to continue to do quite a bit of arithmetic for a long time, and there are some interesting research questions I am sure we will get into as to whether kids still have to do arithmetic in the computer age. But we are beginning to see that this is really the tip of the iceberg, and there is a lot more.

Computers in Education

That computers might have some role in education is not a new idea. I think you would find some early proposals, if not attempts, at computer-aided instruction going back at least 25 years. In this building, the M.S. students in industrial administration have been playing a business game as part of their education since about 1960.

As I will point out in a moment, the introduction of the hand-held calculator is not only an example of computer-aided instruction but an interesting example. But if we look at the educational system today, at the college level, at precollege levels, elementary and secondary, I think we would be very hard-pressed to make a case that computer-aided instruction (CAI) has really made any substantial difference to the educational system. I do not mean by this that useful things have not been done. Some useful programs have been developed particularly in the drill and practice area. And I will mention some other kinds of programs which seem to me in the longer run will prove even more useful and more interesting than these. But CAI simply has not made a great impact on education. And as we move ahead and talk about research on computers in education, it is important for us to ask why. If we don't know why, then finding out is certainly one of the targets we have to mark for research.

If we look at present CAI, there are at least three comments we can make about it. The first is that a lot of CAI fits the horseless carriage description. We simply took over all sorts of things we used to do with kids (for example, there was drill and practice before there were computers, using such advanced technological devices as pencil and paper, and there was the programmed text, which preceded the computer by some years) and we took those procedures and simply put them on a computer.

Perhaps that is cost effective, and perhaps it isn't. That depends on the current cost of hardware and software. But whether it's cost effective or not, it isn't any great shucks. We haven't revolutionized the education system, we haven't even advanced it very far, if we have merely taken the kinds of things we use to do with kids with drill and practice and put them on a computer. If one has any affection for computers (and there are people who have, just as we have affection for yachts and automobiles), one might even say that using computers in this way is abusing them, abusing them because you are not using their real potential, the things that they can really do.

Why use a computer rather than using a pencil or paper? What are the comparative advantages of a computer over pencil and paper? They can all be summed up by the statement that the computer can talk back and the paper can't talk back. Paper only talks when you, the user, write on the paper.

Now, that's a little bit exaggerated. You can cleverly fit a programmed text so that the student gets sent to one page if he answers A and gets sent to another if he answers B. You can do a little bit of branching. It gets very cumbersome technologically after a while, and a computer can do that much better.

The computer has a comparative advantage precisely in the domain of answering back, of doing something in response to the student, of being responsive to important aspects of the student's behavior. But that doesn't come for free. That requires sophisticated software. Computers only respond in intelligent and interesting ways to students if they (the computers) have acquired some intelligence along the way, some artificial intelligence.

And hence the general slowness with which we have been able to create CAI systems that go very much beyond what could be done with the programmed text. The slowness of that development is simply a reflection of the slowness of the development of artificial intelligence, which again is something that people were talking about and doing a little bit about as long as 27 years ago, but which has gotten up to a high pressure within the last five years or not much more.

So point one about computer-aided instruction: the rate at which we are going to be able to introduce it is paced by the level of our understanding of artificial intelligence, because the computers that do a good job at CAI are going to be intelligent computers. Whether artificially or naturally, they are going to have to be intelligent in one way or another.

Second, where schemes of CAI have been introduced, there has been a fairly high rate, I think, of attrition. (If my facts are wrong in any of these things, there are a lot of knowledgeable people at this conference who can correct me, and so I will make outrageous statements tonight and tomorrow you can straighten me out.) But I think there has been a fairly high rate of attrition; that is, systems are built with a great deal of enthusiasm (I could even mention a couple of local examples in which I participated), but when you come back five years later you find that teaching methods are about what they were in 1970. They're no longer using these new technologies.

And when you ask why, there is usually a good reason. The reason is that many of the schemes we develop require an enormous amount of work for their maintenance, for their continual upkeep. For example, we had a number of teachers, here, who are enthusiastic about student-paced instruction. As those of you who have experimented with it know that requires teachers to be able to generate unlimited supplies of interesting problems, and providing new ones. Faculties simply have neither the time nor the motivation to continue to develop these problems. If they have to be developed by hand, after five years or thereabouts of enthusiasm, the student-paced instruction tends to fade from the scene again and you go back to traditional forms of instruction.

Well, here is a place for possible application of the computer. We already have some examples of computer programs that generate problems so that the instructor doesn't have to produce them one by one. The schemes of this kind that I am familiar with that actually have reached the stage of practice have mostly used a number of problem templates, maybe a sizable number. What the computer does is to plug in parameters, to instantiate these problem templates and create specific problems.

That's all right, except again it leaves you with a fairly stereotyped collection of problem forms, and perhaps less imaginative problems than the students should be exposed to over a long period. Here again, if we are to do more automatic problem generation and do it better, the computer programs will need more intelligence, they will have to understand more about the task demands for which they are creating problems.

So we have to ask ourselves, if we are going to do more computer-aided instruction, how are we going to meet the costs of maintaining such systems or man them? How are we going to make those systems exportable? It's complete madness to suppose that materials for each course, computer-aided or otherwise, should be developed at the point where that course is given.

With traditional methods of teaching, we solved that problem with something called the textbook. There are bad textbooks, but there also are good textbooks, and I don't know whether bad textbooks drive out good or good drive out bad. But the fact that textbooks are published, that they are nationally and internationally available, does raise substantially the level of teaching materials over what would be available, if it were a cottage industry, if everybody were writing his own textbook in every single class that was offered.

We have got to develop the kinds of institutions that allow the dissemination of computer software in the same way that textbooks are disseminated.

And that's happening, as we know, from the software efforts of the personal computer companies in the last few years, especially.

It's happening, but it has a long way to go before we have a stable, understandable system for the diffusion of advanced pedagogy in the form of computer programs, so that the diffusion will amortize the investment in producing them and provide the incentives for producing them that is provided by textbook royalties today. Only then will we begin to institutionalize this practice.

We are all aware (and I am not going to solve the problem tonight) of the general difficulty of institutionalizing new practices in education. Almost the last thing that happened to the classroom that changed it at all was the installation of blackboards towards the end of the last century. Perhaps I should also mention the vuegraph, although my friends in the audience know that I regard that device as a backward step, and you do not see one on the platform tonight.

We have very definite problems, then, of advancing artificial intelligence to the point where it can support sophisticated uses of computers in instruction; second, of disseminating materials and motivating the preparation of those materials; and third, and more generally, institutionalizing any kind of change in our educational institutions.

I am rather optimistic about the prospect of disseminating programs, providing we can motivate their production. It is much easier to diffuse artifacts than to diffuse ideas. In the spread of Christianity over a large part of the world, it proved easier to disseminate the cross than to produce human behavior compatible with the church's preachments.

In the case of computer programs, we have something going for us, because the technology is encapsulated in boxes called computers and floppy disks that contain the software. Hence the technology is transmissible. And that hasn't been true of most of other kinds of educational innovations, since, as I say, the blackboard.

Before I leave this topic, I want to say just one more word, because I do not want to leave with you the impression that I think that the only kind of computer-aided instruction has been drill-and-practice programs. That would be unfair to the people who have been working in CAI. As a matter of fact, I mentioned one counterexample, the management game, which is widely used in business schools in this country.

Another example is the artificial laboratory: that is to say, supplementing the physics or the chemistry or the psychological laboratory with data banks so developed and so organized that students can be instructed to design and carry out experiments using them. This technique is not limited to the natural sciences, by the way. We have had a very interesting exercise of that sort in history in our undergraduate college here.

An interesting thing about these documents is that if you try to make a catalog of places where computers are now being used imaginatively in education, where they are now being used in a significant and important way, very few of these applications would have explicitly associated with them the label "computer-aided instruction."

The computer is already being used, particularly at the university level, in an enormous number of ways in instruction, only a tiny fraction of which are called computer-aided instruction. If a psychologist develops a data bank of real or imaginary data for, say, some memory experiments, and then gives his students assignments that require them to use the system to design and carry out experiments and analyze data, he will think of that as part of his instruction in psychology and he won't think that he is doing something mysterious called computer-aided instruction.

At least he won't think that in any environment in which computers are readily available, where anybody can get their hands laid on them. Because if computers are around in sufficient profusion, sufficiently accessible, then imaginative people are going to find all sorts of interesting ways to use them. And these are not necessarily going to be people who are focused on something specifically called computer-aided instruction. They may be just psychology teachers who want to improve their courses or physics teachers who find that they can't do as much in the laboratory with their students as they want, or that for certain kinds of laboratory instruction a simulated experiment would be as useful as a real one.

And so if we made an inquiry around a university like this one, we would find computers being used in all sorts of ways in instruction not only in the engineering and science departments, but, as I indicated, in departments as widely improbable at first blush as history. And we need to find ways of encouraging that because this is probably where a large part of our development is going to take place.

Let me leave then the subject of computer-aided instruction. I am sure that is going to be examined thoroughly and understood better over the next few days. Let me devote the rest of my remarks to two other topics: information overload, and the use of computers for educational research.

Is Information the Scarce Factor?

As we approach the problems of research associated with computers in education, we do need to stand back in order to avoid the horseless carriage syndrome. We need to stand back and try, in a variety of ways, to define what we think the basic problem is. That includes characterizing not only computers and education but also characterizing the society in which these computers are being introduced. Here I would like to try to correct what I think is a fairly widespread misapprehension, probably not shared by any in this room but certainly shared outside this room by lots of people.

We hear a lot of talk about an age of information. We hear a lot of talk about the volumes of information we produce and consume in our society. And certainly there is a lot of information, or at least a lot of symbols going around. (It depends a little on your definition of information as to how much you think information has increased.)

To understand how we should go about dealing with a world in which there are tremendous amounts of information, we have to take into account not only the producers of that information but its consumers, that is, we human beings.

Another way of characterizing our world, other than as a world in which there is lots of information, is in terms of the scarcity of attention that information has produced. If you have some information and some information processors, then the more information you produce, the scarcer the attention to that information, the scarcer the capabilities for processing that information.

We approach research on computers in education in exactly the wrong way if we think that the function of computers is somehow or other to proliferate further the information in society. We have to think instead about the fact that people only live 24 hours a day and of that they usually waste eight hours in sleep, and some insist on eating and so on. Hence, there are only about 16 usable hours a day, and you don't increase that number of hours by increasing **the amount of information that is around. So if computers are to be helpful to us at all, it must be not in producing more information-- we already have enough to occupy us from dawn to dusk--but to help us attend to the information that is the most useful and interesting or, by whatever your criteria are, the most valuable information.**

Computers are only going to help do that if they are intelligent. I don't want a computer pushing the New York Times under my nose every morning. (I have another lecture in which I explain why that's bad for your health.) If I am going to have any transaction with the New York Times at all, I want the computer to screen the Times very carefully and pick out the few items that I should be attending to and, preferably, to attract and digest them and maybe even provide an interpretation of them if it is clever enough to do that--particularly if it knows about the subject of the item that I know.

Computers are just going to add to the din already produced by radio, television, and telephone unless they have enough intelligence to do a large amount of processing of selection and of analysis of the information for us.

And that applies in the application of computers to education as well as to computers anywhere else. We have great technical capabilities for creating data banks. But, who needs data banks? I have the World Almanac, and that satisfies lots of my needs for data.

Who needs a data bank unless there are sophisticated routes of access to it. We don't have a very large library at Carnegie-Mellon University as university libraries go. We are mainly an engineering school and engineers don't read very much, it is said. But nevertheless, there are more books in that library than I am ever going to read in my life. Maybe the library doesn't have just the book I want to read, but I will never know that unless the library is sophisticated enough so that I can find out effectively from it, (a) what I might be wanting to read, (b) whether it's there, (c) how to get it, and so on.

So the task before us is to find out how to make computers intelligent enough so that they will help us conserve scarce attention. That is the real problem in our society today. I don't mean we don't have problems of lack of information, but the kind of information we lack, like what is going to happen to the stock market tomorrow, is not information that computers are going to provide for us.

Computers for Educational Research

Now let me get back to the more specific topic of computers in education for my final remarks. If we are to avoid the horseless carriage syndrome, we must be careful not to assume that the only or even the principal significance of computers for education is in their direct use as an instructional tool in anything that we would want to call computer-aided instruction.

As a matter of fact, I have an alternative candidate, and I hope that our alternative candidate will receive a great deal of discussion at this conference. We have discovered in the last quarter century that computers can be used to model human thinking processes. We have learned that computers are a powerful tool for psychological theorizing, that computer programming languages seem to be the right languages in which to express psychological theories, at least theories about cognition, theories about how people think.

Now, these are mildly debatable points, and we could debate about them a little bit. But let me just assert for purposes of the argument that in fact we have now this powerful engine. What does that have to do with education? It has a great deal to do with the fact that education today as we practice it is nearly theory-free, and we know from other realms of human endeavor, that we can usually make order-of-magnitude progress when we move from a state of complete pragmatism to a stage where our professional practice really has an underpinning of fundamental science.

That change took place in the engineering sciences beginning with Newton probably, but continuing steadily with the growth of modern physical science. It took place in medicine in this century when, for the first time, the practice of medicine was associated with and strongly influenced by an increasingly deep understanding of how the human organism works.

Time after time, when we begin to understand how a mechanism works, then we can improve by very large measure our ability to deal with the problems that arise when the mechanism doesn't work just right.

What did I mean when I said that our practice of education is almost pragmatic? Well, we have a few empirically based principles. We know that people seldom learn things unless they get feedback from their performance. That's called knowledge of results or reinforcement.

We have a second principle, which I am illustrating now not by the content of my talk but by the fact that I am giving it. The second principle is that if you assemble people in a room and spray words at them, some of the words will be contagious and cause fever or other symptoms in the listeners, and some learning may take place. There is a process whereby words produced by some people produce changes in the mental states of other people.

We know how treacherous a process it is. I don't know whether you have ever had the experience, those of you who are teachers, of reading the notes that your students take in class, if you allow them to take notes. It is a searing experience. But we do know that if you allow the process to go on for 20 or 30 years, some changes are induced in the people at whom the words are directed. Now, I think one could allege without too much exaggeration that these are the kinds of principles on which education is based today. The fact that people do get educated shows that the principles work, but certainly doesn't show that they work with any efficiency, as evidenced by the fact that now we are devoting a third or a half of the lives of most Americans and people in other advanced countries to the educational process.

To be honest with ourselves, we don't do that just because those years are required to build the necessary skills. There is also the babysitting function for the lower years of schooling. There is also the consumption aspect of life in college, which some students at least, find enjoyable, so much so that they delay getting their degrees and can't be kicked out.

But nevertheless, we certainly are faced here with a process that is exceedingly inefficient, and inefficient primarily because we don't understand the learning process, although all the signs are that we are very rapidly acquiring a viable theory of it. The computer has already played a very large role in that acquisition by allowing us to model human thinking, human problem-solving performance, human learning, human concept formation.

So I would hope that our attention here, when we talk about a subject as broad as research on computers in education, will not by any means be limited to the things we could call computer-aided instruction but would focus very much on the roles that computers can play as research instruments in gaining this deeper understanding of human thought processes.

Since there are a number of people involved in the conference who have been engaged in that very effort, and I can't believe that they are going to remain silent over the next couple of days, I do have some assurance that this is going to be taken care of.

Computer Literacy

In asking why we should be interested in computers in education, we have a particular challenge that people are now aware of and are talking about a good deal in our society and in other industrialized societies. And that is, we have a concern for something that might be called "computer literacy."

Now, that is an ambiguous phrase, "computer literacy." Everybody is talking about it, everybody wants it. But I should point out to you that it is really not a new problem, because the problem of computer literacy is really a part of a broader problem that has been with us for quite a long time, certainly through most of this century--the problem of quantitative literacy for the population of a technical world.

I go back to the thesis of C.P. Snow, the English scientist and writer who talked about "The Two Cultures"--the culture of humanism and the culture of science and of their difficulties of mutual communication. My concern about this, and the concern of a lot of other people, is that if you have a society that is highly technical, then people who feel that they are fenced out from the technical part of society will feel that they are also fenced out from most of the important decisions that are being made in the society. And they are going to end up in the psychological state we call "alienation."

There are plenty of evidences already in our society of the mistrust of technology (not that there aren't some things about technology that need to be mistrusted, or at least looked at very hard) based on exclusion, or feelings of exclusion, from the vital decisions of the society.

So we have a problem of quantitative literacy, and one part of that is the problem of computer literacy. Computer literacy may even be part of the solution of the problem of quantitative literacy. The computer may give us a means for opening the world of technology to large numbers of people who, for good reasons or bad, would not have it opened to them by the calculus or by other classical mathematics.

I don't think we know yet whether that is the case or not, but there is at least the possibility that the computer is part of the solution of our problem. And if it were--now I am being a little bit optimistic--it would be a solution at a very tolerable cost.

I have made a few back-of-the-envelope calculations of what it would cost to give all the kids in our schools at all levels quite good access to computers today. It would probably not require more than an initial capital expenditure of the order of magnitude of $10 billion, or five battleships out of mothballs, or about one-tenth of the annual expenditure for education in this country. But this is a one-time rather than an annual expenditure. So it is quite a bearable cost of our society to give all kids good access to computers.

Again, we have to worry about the institutional aspects of that. We all know horror stories about computers that have been locked in closets, not because they behave badly but because it was feared that children might behave badly with them. And we have to find some way not only of getting the computers into the schools but leaving them in unlocked rooms.

It was the experience of the universities a couple of decades ago (the ones who went early into the computer business) that if the computers are in unlocked rooms, the students will get at them and the computers will teach the students what computers are all about, or at least they will teach a lot of the students and they will teach the others. And after a while, the faculty will get embarrassed that they don't know, and they will get into the act too.

The first computer on this campus was in the basement of this building (the Graduate School of Industrial Administration). It was in an unlocked room, and that did happen. That is the way that computers were introduced in this institution and in many others at the collegiate level. Although it is a slightly more difficult task, a lot of that could happen in secondary and primary schools and even is happening right now.

As you know, governments are blunt instruments; they are not instruments for fine-tuning anything, as we discover when we try to use them to run the economy. They are blunt instruments, and the main thing they can do is spend money. Here is a way in which you could spend $10 billion with a very good chance that you would make a major impact on computer literacy in this country.

Now, that is very much like the spraying theory. It is a remedy that is not based on any deep understanding of what computer literacy is or how people acquire it. I only propose it because all of us have a feeling of the urgency of doing something in the present situation.

But, of course, in the longer run, we must ask what computer literacy is, what the capabilities are of people in a democracy to understand enough about technical matters, or about ways of reasoning on technical matters, so that they can participate in the basic political decisions of the society. The only way we are going to find that out, again, is by fundamental research on human thought processes.

For example, on the basis of the interesting and important research that has been done on separation of the cerebral hemispheres--Roger Sperry's research and the research that has followed on it--there is a lot of romancing about the two hemispheres. According to this interpretation of the hemispheric research, there are the analytical grubby thinkers who think over on the left side and there are the creative, global, holistic thinkers who think over on the right side.

Well, fortunately, that is nonsense. None of the evidence we have about the two hemispheres supports any such model of the thought processes there. But the fact that such ideas can even be entertained is an indication of how much we still have to learn about human thought processes in order to understand what kinds of thinking people are capable of, whether different people are capable of different kinds of thinking, and what we do about that in education for literacy, whether it be computer literacy or some other.

If I had to pick a single target for research in cognition, it would be the target of finding out enough about human learning and thinking processes so that we could even define, and then begin to approach and solve, the problem of quantitative literacy or technological literacy or computer literacy or whatever you want to call it. Because I think literacy is terribly important for the long-term survival of any society having the kinds of democratic institutions we all want to see preserved.

TECHNOLOGIES FOR LEARNING

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ABSTRACT

This paper explores trends in computer technologies and their implications for learning and education in the future. Learning technologies of the future will be multi-faceted: In addition to conventional drill and practice learning exercises, computer technology will permit us to explore techniques such as episodic learning, learning from examples and simulation, and learning from games. It appears likely, projecting trends in hardware and software technologies, that computational power equivalent to today's supercomputers will be available in a microprocessor system for under $100 by 1990. This paper examines the reasons for such optimism and some necessary conditions for such a system to be realized. Finally, the paper presents a research agenda for a few unsolved problems in learning which may become feasible with the availability of such a low cost supercomputer.

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1. Introduction

Over the past 20 years, I have observed with interest and wonder many of the pioneers who have attempted to use computers in the classroom. Technologies that are available now or are likely to be available over the next three to five years promise the potential for new, exciting methods for teaching and learning. My task is to explore the range of sophisticated applications in education that may become possible with the availability of a microcomputer system more powerful than today's supercomputers and to present the technological advances that are essential before such applications are feasible.

2. Role of Education in a Changing Society

It is known that with rapid changes in technology most of the tools and techniques we learn in school (and college) will be obsolete well before we are ready to retire. Much of what is not obsolete will be either irrelevant or cumbersome for solving problems that arise in day-to-day work-life. The only useful part of the education will have been the acquired ability of "learning-to-learn". The first problem for education then is obsolescence. The key question for future technologies of education is: What is the most appropriate system of education and how can one rapidly obtain and master the new knowledge necessary to perform an unfamiliar task?

The second problem for education is "information overload". There are over 100 million volumes in the Library of Congress, and they contain nearly 100 trillion bytes of text. The roughly 500 daily newspapers in the United States create over a trillion bytes of text every day (table 2.1, below). Professor Oskar Morgenstern once said, "If the publications on physics increase the next hundred and fifty years at the same rate as they have increased over the last hundred and fifty years, the weight of the paper then in existence will be about the weight of the earth." This, in essence, is the paradox of information overload.

One consequence of the information overload is the length of time it takes to master a subject. To be effective, we have to master 3 to 5 orders of magnitude more information than our ancestors in the 19th century. Even in a subdiscipline such as "solid state physics", it is no longer possible to master all aspects in one lifetime. If we were to attempt to master all the books that are in the Library of Congress, we would have to be sitting around, not walking around, with brains weighing about 2 tons. Given our inability to master all the knowledge, most of us have had to seek other solutions. The result has been increasing specialization into narrower and narrower subfields. And yet we know that breakthroughs are often a result of the synergistic utilization of interdisciplinary knowledge.

LIBRARY OF CONGRESS	DAILY NEWSPAPERS
62 CHAR/LIN	35 CHAR LINE
40 LINE/PAGE	100 LINES/COL
600 PAGES/BOOK	6 COL/PAGE
10^7 BITS/BOOK	50 PAGES/DAILY
16×10^6 BOOKS	500 DAILIES/DAY
10^{14} BITS	365 DAYS/YR
	10^7 BITS/DAILY
	2×10^{12} BITS/YR

Table 2-1: Information Overload

3. Learning Strategies

The rapid advances in Information Technology provide us with other options to obsolescence and information overload. We must find more "productive" means of effective and efficient transfer of knowledge to overcome information overload. The printed book (or even the electronic equivalent of it) is no longer adequate for knowledge transfer. To be sure, an electronic book permits us to transfer text infinitely faster than before, but it still depends on a human to acquire, assimilate, and use the knowledge that is in the book. In one lifetime we can only master a fraction of what is known or needed. New forms of knowledge transfer, such as learning of skills from examples and observation, learning of science through entertainment, learning of arts through practice, and learning on demand, provide challenging opportunities for new research in learning. In the following section, we shall examine the technological requirements for some of these forms of knowledge transfer.

3.1. Learning from Examples

A great deal of knowledge transfer in human species happens through example, observation, and practice. When we travel to a place for the first time, we do not read about every aspect of the journey from a book and use that knowledge. To the contrary, we travel accurately by observing signs along the way. Interpersonal relations and other forms of behavior learning are other examples where we acquire a great deal of knowledge through observation. Most of the vocational skills, such as carpentry, masonry, and mechanics, are learned by example through apprenticeship mechanisms. In most of these cases, knowledge transfer occurs not through the conventional symbolic (verbal) communication process but through example and observation. At present, learning from example tends to be a very inefficient mechanism, because it requires direct one-on-one human contact, which is both time consuming and expensive. This in turn restricts the availability of such knowledge to the chosen few who have been initiated into the profession. Computer, communication, and videodisc technologies, for the first time, provide the promise of breaking this log-jam of knowledge transfer for learning tasks which could only be effected in the past by direct contact and observation.

3.2. Learning from Entertainment

One of the biggest barriers to learning is motivation. Going to school, education, and learning day-in and day-out for almost 20 years of one's life is the biggest bore. When one realizes that most of what one is made to learn is either irrelevant or likely to become obsolete, the apathy increases even further.

The worldwide success of the productions of Children's Television Workshop and its role as a creator of learning tools does not require further elaboration. The main lesson for us is that learning can be fun; it can attract children; it can captivate them; and, most interesting of all, the material learned through this mechanism can be long lasting. The only limitation is that TV does not require the interaction of the learner.

The more recent video game boom has the potential of becoming an interactive learning aid. While we do not have many controlled studies of the role of games as a learning aid, there is widespread acceptance of their impact. Lesgold [1982] has a more detailed review of instructional games.

3.3. Learning on Demand

We have already identified technology-induced obsolescence of knowledge as one of the challenges facing future educators. One possible solution to this problem is to view education as a distributed lifelong process where one learns the material as one needs it.

Unfortunately, such learning-on-demand solutions are neither practical nor economical. It is a lot cheaper (and easier) to teach the principles of biology to a class of 30 at some predefined time than to wait for each one to discover that biology is important to some problem they are about to solve and then engage in an educational exercise at that instant. However, the low retention factor of the material learned in school indicates that the current education process principally achieves a "knowing where and what to look for" type of learning. Perhaps if this is set as the explicit objective of early education, then new and creative strategies can be devised to teach children how to "learn-to-learn" and how to locate and utilize information resources.

What then is the role of "learning-on-demand"? Independent of what happens in early education, we all find ourselves in situations where we need to learn new skills, acquire new knowledge, and update our existing knowledge base. There are a number of mechanisms, such as professional seminars, tutorials, adult education classes, etc., most of which use the classroom model for training. Recent innovations, such as self-paced learning, have not achieved widespread acceptance due to a lack of teaching materials, inappropriate technology, and the high cost of providing an instructor to answer questions around the clock. However, many of the recent advances in computer-based education research (Lesgold, Larkin) may make it possible to provide high quality, individualized, self-paced learning systems.

4. Hardware Technologies

Given these potential learning strategies, what computer technologies will permit us to achieve our educational goals, in terms of computational power and economic feasibility? If we consider the power of presently available personal computers that cost approximately 100 dollars, we can estimate the computational power we might be able to get for under 100 dollars in the next decade. If I were to say we could have a super computer somewhat like the Cray-1 for under 100 dollars, you might think that it is too farfetched; I thought so too when I was trying to make such an estimate. But I have extrapolated the technologies and it indeed appears possible to have that kind of affordable computational power in the very near future. Our difficulty in understanding such affordable power is the result of the wrong conception of what a computer is. If we think of a computer as all the peripherals, discs, and other components, then the costs increase proportionately. However, if we think of a computer as a computational engine that has a memory, a processor, and input/output capabilities, we can further isolate the cost of the sheer computational power. If we then ask what kind of technologies are necessary to build such an electronic box for under 100 dollars, an estimate by cost in terms of volume of electronics is as good as any. It has been observed in the past that a cubic foot of electronics costs about 10,000 dollars. Using this as a rough metric, one can assume that any electronic configuration that will fit in roughly 10 cubic inches can be purchased for about 100 dollars. But what can be packed into 10 cubic inches within the next 10 years? Given the current level of computer sophistication, I anticipate that we will have an affordable Cray within the next decade: a 100 MIPS (million instructions per second) processor; a million characters of random access memory; and four million characters of program (read only) memory.

4.1. Memory Technologies

Since 1970, memory densities have quadrupled about every four years. In 1970, we had a 1K (1000 bit) memory chip; in 1974, we had 4K. That trend of development has continued such that today we have 64K memories available on a routine basis. Assuming that trend will continue, we will have 1M (megabyte) of affordable memory by 1990 (Table 4.1, below). A megabyte of random access memory requires 8 chips that are approximately 1 centimeter square each; they are very thin if they have flat pin packing. Since read only memories have roughly 4 times the densities of random access memories, we can have 4 megabytes of program memory, which can hold operating systems, compilers, editors, documentation, help facilities, etc., in another 8 chips.

YEAR	SILICON	BUBBLE
1970	1K	--
1974	4K	--
1978	16K	256KB
1982	64K	1MB
1986	256K(?)	4MB(?)
1990	1M(?)	16MB(?)

Table 4-1: Memory Technology (Idealized)

4.2. Microprocessor Technologies

Processor technologies have developed at a rate comparable to memory technologies. In 1970, we had a 4 bit processor; by 1975, we had increased to 8 bits; and by 1980, we had 16 bit processors. If the trend continues at that pace, we will have 32 bit processors by 1985, and 64 bit processors by 1990

(Table 4.2, below). The computational power of these processors, if measured in millions of instructions per second (MIPS), has also grown by a factor of 10 each five years since 1970. The 4 bit computer of 1970 was what we called a 10 KIPS machine (10 thousand instructions per second), which was the equivalent of an IBM 1620 that cost 100,000 dollars in 1960.

Each five years, the power has increased by a factor of ten, such that by 1980 we had a 1 MIPS machine. Extrapolating that same trend, we could have a 100 MIPS computer by 1990. In November, 1982, Hewlett Packard announced a personal computer using half a million transistors which is a 20 megahertz, 32 bit processor with a 50 nanosecond clock time. Scientists at other companies are working on picosecond gate-delay technologies. It is entirely possible with 200 MHz clock times will be available on a priority basis within the next 4 to 5 years. These processors, however, will be expensive.

Nevertheless, I claim it ought to be possible for us to have a 100 MIPS processor, a megabyte of memory, and four megabytes of read only memory, plus all the required circuitry, at an affordable price by 1990. That kind of processor will require roughly 20 to 25 chips, which will most certainly fit into a package of 10 cubic inches. The question for us as educators is, then: What kinds of experiments can we create to use that much processor capability, that much raw computational power? I think the answers to that question contain exciting concepts that we should speculate about and plan for now, rather than waiting for the technologies to arrive and then asking ourselves what to do with the power.

YEAR	DATA PATHS	POWER	# OF TRANSISTORS
1970	4 BIT	10 KIPS	500
1975	8 BIT	100 KIPS	5,000
1980	16 BIT	1 MIPS	50,000
1985	32 BIT	10 MIPS	500,000 (?)
1990	64 BIT	100 MIPS	5,000,000 (?)

Table 4-2: Microprocessor Technology (Idealized)

4.3. Output Technologies

Currently, there are a number of output technologies on the horizon. Most of us are familiar with graphics and color; there are about a half dozen color and graphic technologies available now, many of which are both inexpensive and exciting. Many of the small personal computers already come with an image buffer. Some come with microcassettes, small dot-matrix printers, four line LCD displays, and regular keyboard devices. Such systems are available for approximately 700 to 1000 dollars. On a priority basis, 8 line, 80 character LCD displays are already available within certain companies.

Video disc technology is already being used in a number of laboratories. Though the creation of software for video discs is time consuming, they provide the capability for a large number of discs with the same software, or course material, that can be distributed throughout the country at very low cost. Each disc costs approximately 15 dollars, and can contain roughly 15 to 54 thousand images. Further, you can access the discs randomly.

There is a new technology called compact audio disc technology, which is just being introduced in Japan and Europe; it is not yet here in this country. With this technology, a small disc, smaller than a floppy, can store roughly a billion bits of read only memory.

There is also HDTV (high definition TV) technology, a 1000 by 1200 line color display that is already being developed, at least the standards are being worked on. It is estimated by 1990 there will be such a commercial TV receiver, probably all digital internally.

Speech output technologies are already here for simple tasks. We have a single board computer into which you can type any English sentence and it will produce an equivalent speech sentence of acceptable quality. This is now a commercial product.

4.4. Input Technologies

As for input technologies, again the question arises: What can we afford for under 100 dollars? Today, we already have fairly elaborate input devices that are very affordable. For example, Casio markets a low cost equivalent of an electronic organ; the device has approximately 80% of the functionality of an electric organ that would have cost 1000 dollars a few years ago. The device is available for around 50 dollars. It has about 50 keys that can provide many functions. Further, it contains a clock with an alarm, a calculator, an LCD display, and a speaker. That is the kind of media-rich input capability that we can anticipate within the next decade. And given its low cost today, how much will it cost in the future? If we consider the cost decreases for other products, such as calculators and digital watches, it seems safe to say such a device will become even more inexpensive over time.

Therefore, it is not unreasonable to assume that we will have 100 MIPS of computational power and fairly sophisticated input/output devices for under 100 dollars by 1990. There are, however, many issues involved. It is hard to say what the real cost will be; technological projections are always difficult to make. Whereas we thought earlier that we would have larger processors, we have, in fact, achieved more integration and functionality, such as integrated processor, memory, and I/O electronics, on a single chip. So, there may be different architectures in the future that will provide greater functionality without increasing processor power.

5. Software Technology

I am going to bypass programming languages in this paper because Alan Lesgold covers the issues very well in his paper [1982]. There is one issue I would like to raise, however. We seem to be suffering from the illusion that programming computers is important and that all students must therefore have programming literacy. I want to differ with this view, however, because over 99% of the routine, common uses of computers do not require programming knowledge any more than driving a car requires mechanical knowledge of the workings of the automobile. Most people will use computers to assist them in ways that will not require programming knowledge. Therefore, we need to spend more time thinking about the types of assistance we will want from computers, what we want them to do, not how to program them. I am not saying that no one should think about programming; I am saying that the questions about programming are by no means the right or the only questions to ask when considering the future of computing in education.

5.1. Operating Systems

When we consider large operating systems, which may network together an entire nation, we must consider the purposes people will use such systems for. One thing we will most certainly need is distributed operating systems. In particular, we will need mechanisms for remote procedure calls that will allow us to share programs, perhaps, on a nationwide basis. For example, suppose I do not have a particular program that I need, but Herbert Simon has the program. Will I be able to call that program and run it on my data? Further, there are issues of inter-process communication: Some problems are too complex for one person to solve. But, if there are ten people who can work together to solve a large problem, how can they pool their creative talents? Thus, mechanisms for interprocess communication are essential for larger shared systems such as educational systems.

Then there are issues of transparent distributed file systems: How do we make our interesting and valuable data accessible to others who might benefit from it? If we have to know exactly where particular sets of data are located in terms of accounts, file names, etc., then they are not very accessible; in fact, the data is completely useless to people who do not know methods for accessing such valuable information within the near future.

5.2. Data Bases

Perhaps the most important issue is that of data bases. The question is what kind of data bases do we create? In general, there are a number of problems we do not yet know how to deal with. Given the information overload, how do we structure data bases such that retrieval will be accurate and efficient. An example of the problem is illustrated by the fact that the manual for the Timex Sinclair 1000 weighs more than the computer itself. The manual contains 10 times the information that the computer is capable of holding in its random access memory! There is absolutely no reason why computers cannot be self-describing. You can put the same number of characters that the manual contains in [illegible] number of read-only chips, perhaps two or three; then, with a small amount of software, you could access it. The cost should be about the same as the cost of printing and distributing the manual. Further, you wouldn't need to carry around a manual. So, one of the rules for people who design user interfaces is that the user should not have to spend very much time learning to use a new design. There are many issues concerning knowledge banks. We need new techniques for rapid indexing, intelligent indexing, and other tools that are useful but not currently available on any broad scale.

5.3. User Interfaces

Most present user interfaces in systems are very primitive. We need forgiving interfaces that will accept mundane errors on our part without responding with an error message that forces us to correct syntax or spelling errors. We must also develop media-rich interfaces, computers you can speak to and hear, touch sensitive pointing devices, etc. There is no reason that future computers cannot be media intensive. You should never have to use a keyboard to communicate with the computer; in fact, in the User Graceful Interaction Project we forbid the programmers to use their keyboards. If they have to rely on the keyboard then there is something wrong with their interface design. We need to design interfaces so they can be personalized to our individual needs to respond to a user according to that user's needs, rather than providing a generic response. They should not explain answers to problems in the same detailed way as the manual; they should provide a context specific answer that is immediately usable.

6. Research Agenda

Given these advances in technology, how can we use them to enhance the process of education? What are the kinds of uses that might be useful and stimulating? So far computers have been used to assist in reading, writing, and some science courses. There are many other areas that might also benefit through effective use of this technology. How can we use computers to help students learn art, drama, music, or foreign languages? What does it mean to learn history or geography? Learning geography by reading prose is not very meaningful. A true geography lesson should allow a student to see, smell, and feel the terrain. Similarly, a history lesson should be more than the memorizing of facts, names, and dates. Rather, a student should be able to participate in historical events, or at least observe them, and feel them, more realistically through simulation. It is more important for students to gain a sense of what happened than it is for them to memorize facts and numbers. Knowledge gained through observation of participation through seeing and doing appears to be more long lasting. Such student participation requires artificial labs to simulate the events. Technologies are already available to provide us with many of the tools to achieve such new forms of learning. However, there are several large research projects we may have to undertake before such ideas become practical and economical: the creation of a World Knowledge Bank, and the development of Knowledge Based Simulations.

6.1. The World Knowledge Bank

Even though we can rapidly access much of the knowledge in a book if it is in an electronic form, all books are not available in that form today. Though there are great libraries, such as the Library of Congress, few of us have regular access to them. The privileged few who can frequent such libraries can only read a minute percentage of the books in a lifetime. We need to develop technologies that will allow us to convert books to an electronic form so that more people can access the knowledge. We need to develop technologies for scanning, character recognition, and language translations. Though these technologies are not highly developed today, they can be realized in the near future if given the right impetus.

We need to create a knowledge bank that contains the procedural knowledge of skills and vocations. Such a bank should provide us with the information necessary to build a bridge, run a dairy farm, lay bricks, repair a TV set, or any of the other skills we might need at any given moment. The information should be useful, accurate, and easy to access.

We should be able to acquire the knowledge from ancient manuscripts. There is a wealth of untapped knowledge in these manuscripts that could provide us with abundant insights. Perhaps we could learn from them history as it actually happened.

We need technologies for indexing into very large data bases, and we need technologies for very large archival memories. Though such technologies are not realized as of yet, they will eventually arrive. Exactly when they will arrive is not clear; but it is very clear that when they do arrive the Library of Congress will fit into a very small space, because these will be molecular level memories where features are measured in Angstroms.

6.2. Knowledge Based Simulations

In general, we need to be able to create simulations for training and education. In the Robotics Institute of Carnegie-Mellon University, we are involved in a project to simulate the workings of a factory. One company discovered that it was wasting three million dollars per year to train twenty five new employees. Since the company was training the new employees on the actual manufacturing lines, each mistake by a trainee wasted valuable raw materials. Through simulation, new employees can be trained to operate these manufacturing processes without the risks of loss. Once these employees have completed their simulated training, they can enter onto the factory floor with a higher level of competence. It is estimated that they will then make only ten percent of the mistakes they would have made originally. This type of simulated training has been used for many years to train pilots, who cannot afford to learn through mistakes while flying. Once available on a wider basis, simulation systems will be a major boon to education; virtually everything we need to teach can be simulated. Particularly complex processes that could benefit greatly from simulations include design, planning, and logistic support.

Allan Kay of Atari is interested in the concept of an active encyclopedia. He wants to create an entire set of encyclopedias in electronic form. When you access the information from this conceptualized system, you would not get prose; you see a simulated story.

7. Conclusion

If the human being is superior to other species, it is not because of the genetic material we inherit, not because of the capacity of the human brain, but because of our ability to create artifacts which can acquire, store, transmit, and (more recently) manipulate knowledge. In order to quantify and substantiate this observation, I would like to explain what happened during evolution using computer terminology.

Let us compare the genetically inherited information of bacteria and express it in terms of information storage. The genome of bacteria would require about 10 million bits of memory and that of a man would require about 12 billion bits of memory. Expressed another way, the information in the genome of a bacterium would fill one 500 page book while that of the human would require about 1200 books--not an enormous amount considering how complex we think we are compared with bacteria which have no sensors, no brain, and no ability to communicate except genetically.

The human brain is estimated to be capable of storing roughly 3×10^{13} bits of information. That means, even if we can utilize one hundred percent of this capacity, it will hold less than 10% of the information in the Library of Congress. A more serious problem is that the information contained in the brain can only be transmitted through personal contact or instruction. Thus aquatic mammals, such as the porpoises and whales whose brains are fully as sophisticated and about ten times larger than ours, are locked in an unfortunate situation: They can't escape from the present to use their past and, therefore, are forever restricted to information transfer they can achieve through direct contact in one lifetime--not unlike the Aryans communicating Vedas by recital from generation to generation in 3000 B.C.

The human was the first (and so far the only) species to break the barrier to communication and transfer of knowledge through the invention of a multitude of artifacts which might otherwise have required genetic solutions for survival. For example,

> If he wanted to keep himself warm, he did not have to change his genes to grow a fur coat; he made a fur coat; he built shelters; he learned how to use fire. If he wanted to fly, he didn't wait to grow wings to fly; he invented a machine that flew in the air. If he wanted to go into the water, he didn't wait to grow gills or a new breathing apparatus; he simply invented a ship. If he wanted to become resistant to disease, he did not have to change his genes; he created vaccines and wiped out polio and smallpox (Spiegelman, 1979).

The computer is perhaps the ultimate artifact created by man. In addition to providing access to world knowledge instantaneously, as a symbol processor it provides us with the potential to convert passive knowledge in books into an active form. Thus it will, some day, be no longer necessary to spend days assimilating information that we will be able to access from the World Knowledge Bank in microseconds. In short, each person could have an intelligent assistant, advisor, and consultant, which will surely change the entire role of education!

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PARADIGMS FOR COMPUTER-BASED EDUCATION

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Contents

This chapter is partly a general summary of emerging instructional paradigms and partly some personal viewpoints on where to start in exploiting the computer revolution for education. My primary bias is to concentrate on forms of instruction that are possible only with computers and then to ask what is needed for educators to begin designing and using those forms. Thus, this paper begins with a discussion of what it is that excites me about having substantial computer power in the classroom. The next section sketches new issues of instructional psychology that should be attended to in the design of computer-based instruction. After that, there follows a brief discussion of issues of motivation that are relevant to computer-based education. This is followed by the main body of the paper, in which recent computer-based instruction paradigms are discussed. The concluding section deals with issues that arise with any new medium of expression: understanding its basic capabilities, developing artistic standards for the medium, and developing a sense of what well-crafted products within the medium should be like.

I.O WHAT CANNOT BE DONE WITHOUT A COMPUTER?

It is common among critics of extant computer-assisted instructional products to hear complaints that most current commercial programs are nothing but automatic page turners. Indeed, a perusal of the software sold for school use produces quite a few exemplars of a form in which exercises found in workbooks are displayed successively on a video screen. Usually, the readability and graphic quality of the exercise is poorer than in the workbook and the acceptable student responses greatly restricted. Short texts in capital letters with multiple choice responding is quite common. Yet, teachers often welcome such aids; their novelty results in some students spending a bit more time spent in drill than would otherwise be the case, and the very presence of computers in a school building relieves parents who worry that their children will not be adequately prepared for the information economy in which they will have to live.

We know that these reasons are poor ones. The novelty of the machine wears off quite quickly unless the machine is delivering an interesting message. Being exposed to computers by using them trivially is no more preparation for a career in an automated world than watching soap operas about doctors is for a career in medicine. The research world must provide leadership and do some of the analytical thinking that will help educators know what is worth doing with computers. What follows are several general areas in which computers can add more substantially to the quality of education.

I.A. Rapid Diagnosis

One major capability that a computer can have, given adequate software, is to rapidly diagnose specific sources of student errors. Such diagnostic capability can be used in many different ways. The simplest possibility is providing the teacher with an assessment of where different children are in their acquisition of skills. Such data, perhaps gathered from observation of children's playing of games designed to provide practice opportunities, can help in grouping children for small group activities and can occasionally reveal specific skill weaknesses that might have passed for general negligence. The BUGGY program developed by Brown and Burton is a good example of this sort of capability.

It is possible to go quite a bit further, though, and to use computer-based diagnosis to support coaching and tutoring capability. The WEST tutor by Brown and Burton illustrates this type of approach. WEST compares the student's performance with a model of expert performance and then generates a list of skill components that are likely to be missing in the student. It then has the difficult task of deciding how to intervene in the student's game-playing in ways that might foster acquisition of the missing skills.

A substantial extension of this approach might take account of how psychologists currently think cognitive skills are learned and might make diagnoses that differentiate the need for conceptual acquisition from the need for practice of procedural skills. Such a system does not yet exist, but is a feasible research goal that recent advances in computer technology and computer science make possible. A second research goal of this sort might be a capability for diagnosing basic verbal, quantitative, and spatial aptitude levels and adjusting the formatting of displays and texts to individual differences in aptitude. The reality of elementary and secondary education is that many teachers, in teaching the curriculum, are operating perilously close to the limits of their own understanding. Consequently, diagnosis, which tends to require sophistication well beyond the skills being taught, is hard for them, and a computer assist would be a breakthrough.

I.B Quick Response And Attentional Focus

A second capability of computers, and one in which more progress has been made, is the ability to respond quickly to the student and thereby keep his attention focused on the task at hand. A variety of instructional games are starting to appear that have this property, and other formats are also being designed. However, there is much left to be done. In general, much more sophisticated software and hardware will be needed if systems are to be truly responsive and attention-demanding. Characteristically, existing CAI systems make decisions about prompting the student at too microscopic a level. Rather than independently assessing the rate and quality of responses by the student, they are able only to branch to a prompt routine if too much time elapses on a given frame. This sort of context-free decision making leads to various frustrations, such as being dunned incessantly on a frame while you look up a word in the dictionary or not being allowed to proceed to the next frame because the designer thought you should spend at least n seconds on each line of text. Here both motivational research and a small amount of technological development are needed for computers to become more useful.

I.C. Improved Laboratory Experiences

Computers can greatly enhance student opportunities for laboratory experiences. Educators value laboratory situations. We know that some concepts are best learned from concrete experience. We also know that concrete problem situations allow useful exercise of newly-learned facts and rules. However, there are many barriers to effective laboratory facilities, including the cost of the necessary manipulables and supplies. Certainly, the computer can decrease the costs of laboratories and can permit laboratory experiences that are tailored to individual needs. It can provide simulations of experiments that might be dangerous in real school settings and can bring those experiences to a wider range of students.

For example, there are many students who have simple motor problems in the lab. There are others who lack basic intellectual aptitudes and have difficulty getting through the specific instructions for an experiment and little likelihood of making grand inductions from the experience. More important, there are many situations in which physical limitations limit effectiveness even for the better student. For example, most students in elementary school are briefly exposed to Dienes blocks or some other concrete manifestation of place value. However, few are able to do significant exercises involving four or five places. The mechanical problems in handling 10,000 unit cubes makes such extreme exercises impossible. Yet, there is indication in some of the recent mathematics learning research (e.g., work in the Greeno-Resnick group at my institution) that the concrete experiences that underpin understanding need to be richer and more extreme than is likely to result from current classroom experiences with these manipulables.

The computer can handle thousands of cubes in a screen display. It never drops test tubes nor bumbles procedures such as titrations. Even hard-to-stage events can be repeated if this is helpful. In the face of constraints produced by time limits, motor coordination limits, and aptitude limits, the computer-based lab experience can succeed in doing what would otherwise be impossible.

I.C.1 The Physically Difficult or Impossible

It can also do the impossible in another sense. Physical demonstrations must follow the physical laws. However, students often hold views of the world that are incorrect, and they would benefit from confronting the specific differences between their views and currently accepted ones. The computer can illustrate both accepted reality and the world as a student sees it. On the computer screen, the sun can orbit the earth, the laws of motion can be repealed, the gambler's fallacy can temporarily hold true. This provides important teaching opportunities. It also raises the question of how to teach young children that computers can provide both important reality tests and extensions of our fantasies, and how to tell the two apart.

The computer can also offer multiple viewpoints on a phenomenon, as shown below in the discussion of the physics laboratory programs. If students can't see something important in a direct animated imitation of a phenomenon, a variety of graphical and sound aids can be offered as adjuncts. When the goal is understanding, the computer can make these displays for the student. In later stages of learning, it can help the student make graphical aids for himself.

I.D Computer Literacy

For parents, and maybe for all of us, the ultimate reason for having computers in schools is to teach students some of the basics of an age they are entering, in which information will be one currency in our economy and in which many occupations will require the use of computers to extend one's information manipulating ability. For this to happen successfully, schools need assistance in sorting out which aspects of current computer usage will provide good background for the long term.

There is a temptation to view computer literacy as the equivalent of industrial arts classes for our times, as insurance that our children will have jobs. The danger is in being too short-sighted. When my father's school board wanted to know what to teach in industrial arts classes, they asked local industrial leaders where there were jobs for which not enough people had the right preparation. He was taught woodworking, drafting, and sheet-metal skills which were good preparations for jobs in an industrial midwest city; the same skills were useful for more than a generation.

If that school board used the same techniques today, schools would, to a large extent, be training students to do exactly what automated programming systems will be doing for us in only a few years. In areas with run-down industry, the call might even be for high school graduates who can keypunch or program obsolete computers. Perhaps, with some luck, the high-tech coastal areas would be more foresighted, but even there, very temporary skill needs will drive industrial demands for computer training unless we have a clearer national sense of where the information-processing world is going. To a large extent, our whole society lacks the ability to keep up with the computer revolution. Finding the right mix of skills to teach our children is a task to which the best available talent should be applied.

If we fail to provide any computer literacy training, our children will be doomed to the lower portion of the socio-economic scale. If we provide only the veneer of skill needed to fit into a current job or to be a more likely consumer of current home computers, we provide a few years of job security but only an illusion of immunity from obsolescense. Fundamental understanding of how to plan the solution of information-processing problems is what needs to be taught, and much research is needed to develop exemplary prototypes that the commercial world can tailor to local needs.

II.0 NEW ISSUES OF INSTRUCTIONAL PSYCHOLOGY

This is a presentation about instructional methods. However, I feel the need to briefly outline some of the emerging principles of instruction that can inform method selection decisions. Just as the last technology of schooling, which used teaching machines, depended on behavioral theories, the computer technology will exploit cognitive theory.

II.A Automaticity Theory

Our understanding of skilled performances such as reading has matured substantially. While folk wisdom tells us that practice makes perfect, we have lost sight of this in our schools. Much of education is organized around achieving the lowest levels of learning. On tests, we ask students to be correct 70 or 80 or at most 90% of the time. However, correct performances at the limits of our capabilities depend upon very high reliability and efficiency of lower level skills. No one, for example, can be correct 80% of the time on a history test if he can only recognize 80% of the words or if he must concentrate on word recognition at the expense of integrated understanding. Recent efforts in the psychology of reading problems and even, to some extent, in work on math learning has developed a clearer picture of the need for concentration on overlearning or automation of the simpler subskills that underpin more complex performances.

II.B Pedagogical Theories

A second area in which progress has been made is the integration of theory from developmental psychology with the more static accounts of competence that emerge from cognitive research on learning and performance. We now realize that sophisticated understanding of the world does not simply accrete as specific principles are learned but rather that there are qualitative differences between understanding at one level of learning and understanding at a higher level. Glaser has suggested that temporary organizations of partial knowledge may need to be taught to the child. That is, in order to exercise the learning that has already taken place, it may be necessary to provide the child with a coherent organization for what he knows, even if that organization does not perfectly match more sophisticated views. He calls these temporary organizations pedagogical theories. An example might be providing a more Aristotelean theory of physics to a young child who is not yet ready to understand Newton's laws or using the metaphors of Galilean relativity to help someone who is not yet ready to handle the special theory of relativity.

Research will be needed to clarify the types of pedagogical theories that should be used and the circumstances under which we should avoid such approaches.

II.C Tailored Coaching

Perhaps the most important advances have come from work aimed at developing tutoring or coaching systems. Building a computer-based tutor forces many issues that cognitive psychologists have otherwise avoided. Some of these issues are so close to the margin of what psychologists know how to study that they are also philosophical questions (e.g., what does it mean to understand a mechanism? what kinds of explanations do teachers tend to offer, and how adequate are they?). They represent simultaneously the highest levels of basic abstraction in cognitive research and the most applied work. Understanding what a good electronics technician knows when he is able to diagnose equipment failures or what a person must know to assemble a mechanical device has immediate payoff for a specific applied task and general payoff in principles for attacking other tasks. The WEST and ARITHMEKIT examples discussed below elaborate on what is learned from building tutoring systems.

II.D Articulating Practice And Conceptual Learning

There is an area of cognitive psychology that is not well developed but that we will need if we are to produce the best intelligent computer systems. We need a coherent theory of instructional design. For example, we know that subskills should be practiced at length. We also know that certain sorts of exploratory worlds, especially when equipped with a tutor, can provide deep levels of understanding. Exploration and practice need not be disparate activities. We must resist the academic tendency to make lists of all the separate kinds of things that might help students learn and then force students through one such device after another. It should be possible for the very best designers we have to build systems that integrate several kinds of instructional goals into a single coherent whole, that articulate practice and conceptual learning possibilities. We will see the beginnings of such designs in the demonstrations for this meeting, but substantially more in the way of pace-setting prototype systems is needed. Perhaps an instructional systems architecture competition is needed--along the lines of the ARPA speech understanding competition of the seventies.

This is a conference on computers in education, and our recommended agenda should focus on that specific need. However, we should bear in mind that the best of such research will include some projects that are also good basic science, and that we need that basic science at least as much as we need specific software.

III.0 MOTIVATION

Substantial work on motivation issues related to computer-based education is also needed. Students will do certain tasks on certain computer systems that they will not do otherwise. Theory needs to be developed and tested that can explain the motivational differences between one system and another. Such a theory, I suspect, will be an amalgam of current social psychological work, traditional views of reinforcement and feedback, and principles of cognitive psychology.

We need to better understand the differences between reinforcement through rewards that are not directly related to what is being learned (i.e., points for correct performance, or a chance to play a valued game) and the reinforcement that comes from knowing that one is becoming more successful in a skill. We see, in athletic coaching, an even-handed mixture of the two kinds of motivation. Social reinforcements are offered, but part of the reward in practicing swimming or football skills comes from knowing that one is moving closer to specific performance goals, winning races, winning games.

My personal suspicion is that many students who might find it rewarding to know that they are becoming better writers or better problem solvers do not actually recognize that success. What is the writing skill equivalent of winning a football game? Perhaps it is recognizing that your latest work is more fun to read than the stuff you wrote two months ago. Surely, it is more than getting five points on a scoreboard display. We need to know how it differs and how to make such successes evident to the learner.

We also have, in the computer game world, a chance to understand reinforcement schedules at an entirely new qualitative level. The Skinnerian teaching machine provided a reward within about a second after a response. Each reward was quick, but the overall pace of performance was not all that fast in many cases. Computer games seem rewarding in part because one gets immersed in them and seduced by the pacing of action. The effects are not at quite the same qualitative level as in Skinnerian reinforcement schedules. Work is needed to understand these effects so that we can use them better and with more certainty about possible side effects.

IV.0 REVIEW OF NEWLY-EMERGING METHODS

Having presented several themes that I think are important to our deliberations, I now take up my primary charge, reviewing some of the recently emerging forms of computer-based instruction. The striking property of these more novel forms is that they provide, in one sense or another, an environment over which the student has considerable feeling of being "in charge." The responsiveness of any computer system, including these instructional systems, to individual needs depends heavily on a system organization that permits several relatively independent forms of computation to be going on simultaneously, with the student and perhaps the teacher able to interact with any of them. Both students and teachers will sometimes need to examine and alter any aspect of the system, including the system's knowledge of its own state. The importance of this requirement for multi-tasking capability will emerge as the specific forms of instruction are examined.

IV.A Instructional Games

Instructional games can be a powerful force in education. Some learning requires activity that is generally dull and repetitious. An obvious example is practice of simple verbal skills, such as correct pronunciation of a foreign language or word recognition in beginning. In addition, though, there are concepts to be learned that are hard to absorb off the printed page or from a lecture. Instructional games can sometimes increase students' ability to get necessary practice done; the best games also provide learning experiences that are difficult to create in less realistic environments. What follows are descriptions of several types of games.*1

IV.A.1 Games As Filters For Prescribed Practice

However, there is considerable evidence that intellectual skills also require considerable exercise before they become fully effective. In mathematics, research efforts are beginning to achieve a rapprochement between understanding and drill; in reading, evidence accumulates for the dependence of the "intellectual" aspects of reading on automation of lower level skills, such as word recognition; even in domains such as radiology, the role of highly overlearned perceptual skills in the course of diagnostic reasoning is becoming apparent. More important, substantial theory (e.g., Anderson, 1982) has been developed to explain the specifics of practice effects. Consequently, even though practice is a less glamorous goal for computer-based education, it is one that should be vigorously pursued.

Practice-providing games need several properties. First, they must demonstrably provide the practice for which they are targeted. Second, they must be motivating enough to keep the student engaged in effective practice. Third, they must convince parents and teachers that they provide a specific practice function.

<u>Examples</u>. Two short examples help illustrate these points. The first is a game under development by my colleagues Isabel Beck and Steven Roth at the Learning Research and Development Center. This game is designed to provide opportunities to practice differentiating words that have similar starting and ending consonants but differing vowel centers (e.g., bet, bait, bat, beet, etc.). The game is similar to certain electronic arcade games in certain respects. There is a maze covering the board, with words located at various places in the maze. The child's task is to steer a small creature around the board with a joystick. The computer speaks a word, and the child wins points if he steers the creature to that word and then presses the joystick button. Additional elaborations and complexities are built in, allowing the game to be played at many different levels (for example, the faster the response after a word is spoken, the more points are earned; wild cards can be used for any word, but they will not count unless a related phonics performance is done correctly). The game can be shown to require performances that are consistent with current practice goals in reading for elementary school children.

*1 Games also can function as simulations of real-world environments that the student is studying (e.g., business games, war games, etc.). I treated simulation as a separate topic, which is taken up below, because it imposes a separate [illegible] of requirements on authoring environments.

However, it will be successful only if it keeps children's interest. This it seems to do. Intuitively, I can see many similarities between this game and games like Monopoly and PACMAN. However, we need better research on what it takes to make games such as these motivating. We also need to address the question of whether children who get regular access to such games will still be able to learn in more traditional environments or whether certain games somehow destroy the mental discipline needed to learn from teachers.

A second example is one of the components in a computer-assisted writing instruction project at Bolt Beranek and Newman. A BBN group headed by Allen Collins and working with outside consultants such as Jim Levin, has developed a computer-based classroom newspaper. Students can function as both writers and editors of articles in this newspaper and have an array of word processing tools available that allow them to concentrate on developing and editing compositions. The final products can then be printed as a classroom newspaper that parents and friends can read. Such a system provides additional motivation over traditional homework assignments and also optimizes students' writing time by providing tools that facilitate the drafting and redrafting process. Work is also in progress at BBN and elsewhere on coaching aids that help students figure out what to write about in the first place.

IV.A.2 Games As Discovery Environments

The topic of games as discovery environments overlaps that of the computer as a laboratory. In both cases, the game functions by creating situations in which the student confronts problems from which he can discover important new principles. In the laboratory format, these situations are explicitly created according to an instructional sequence. In the game environment, the overall game is engineered so that students often find themselves in such situations no matter which choices they make in playing the game. In essence, the game adds a feeling of being in charge to the experiences that other laboratory environments might also provide, at a risk that the student won't always make instructionally optimal choices.

I will mention only one example. Ann Piestrup at The Learning Company has followed up earlier NSF-sponsored work in developing a game environment called Gertrude's Secrets. The game environment is designed to teach simple logic and set concepts to young children (e.g., the set of blue squares is the intersection of the set of blue things and the set of squares). There are a number of ways in which the environment stimulates exploration by the child while assuring that given sufficient exploratory time certain concepts will be acquired. The environment is similar to games such as Adventure in some respects. At the start of a session, the child controls a cursor with a joystick (the program works without a joystick, but not as well) that can be moved anywhere on the screen except through "walls." Around the edges of the screen, there are several openings in the walls, giving the appearance of a floor plan of a room. Moving the cursor through an opening produces a screen depicting an adjacent "room."

Signs along the way point toward games one can learn to play. Each game is in a suite of three rooms, one to play in, one that illustrates the game in action, and one that contains text with instructions. There is a helping personality, Gertrude the Goose, who brings the pieces for each game, provides a "treasure" after each game is finished, and stores the treasures (pictures of valued objects) in a "treasure room." Two rooms provide resources for the student to modify the game him/herself, by producing new shapes to be used as game pieces.

Several devices seem to increase the effectiveness of this game. First, there are multiple levels of complexity, stimulating the child who has played before or who is more gifted as well as the slower or newer player. Second, there are elements of student control: if you don't want to make Venn diagrams with circles and squares, you can make some with spiders and snakes instead. If you don't want to play one game, you can play another. Third, it is easy to get help; you just move your piece into the help room. Fourth, the designer is a good artist, making effective use of color, graphics, and, most important, blank space.

There are not many Ann Piestrups around, and it is worth asking whether it is possible to move beyond the current stage in which there are two or three real geniuses designing instruction with the rest of us believing in everything they do because our conviction of its overall value is not matched by a clear sense of which specifics matter. We might want to have research available on the kinds of motivational properties Piestrup has used. What sorts of choices are important for motivation? How many options are the right number? How do you assure generalization from snakes and spiders to triangles and squares?

Most important, we must realize that Piestrup has only begun, and the novelty of her work hides future problems. There are currently eight worlds like the one just described. This means that the total set of choices of "rooms" may already be on the order of 200, with new ideas still being developed. Will a child find his way in the game environment of the future that has hundreds of "rooms"? I think not. Soon there will be need for great intelligence in these games, so that the rooms a child finds nearby are ones consistent with not only his interests but also some instructional goals.

IV.A.3 General Issues For Game Development

Games are used as instructional devices in large part because of the likelihood that the student will be more motivated to play the game than to engage in other learning activities. Nonetheless, games will be most useful for instruction when the motivation to keep playing is intrinsic to the game, (in the sense of Malone, 1981), and hopefully even to the skill for which the game was written. Ideally, students should learn to recognize improvements in their skills as "success," without need for a superimposed artificial layer of reinforcement.

It can be safely assumed that there will be a continuing need for an arsenal of motivators which, hopefully, will be used sparingly. In the sections that follow, some of the issues this raises are explored. Of overriding importance are several general concerns that may require research. We need to make some decisions about the likely capabilities of software built to run on different levels of hardware, so that schools can have some sense of what they will gain or lose by purchasing small-memory, 8-bit machines; 64K 8-bit machines; 16-bit machines with 8-bit data paths; true 16-bit machines; and even larger ones such as the lisp machines starting to appear. Work is also needed to develop standard toolkits, or authoring environments for different levels of hardware. Hopefully, these authoring environments will lead to some upward compatibility of software, allowing old tools to be used on new machines. A major purpose of such toolkits is providing easy access to standard motivating devices, such as those next discussed.

IV.A.3.a Sound And Light

Even a cursory look at successful arcade games calls attention to the variety of surprising sounds and animations that are used to entice and hold the interest of players. At present, most games in arcades are based upon extremely small amounts of memory and processing power. Thus, any of the devices in such games should be readily available to an instructional designer. The only task for the builder of software authoring toolkits is to make it simple and straightforward to use them.

A voice chip of common words and game noises should add very little (less than $250) to the price of a system. What is needed is a facility that would allow an author to listen to a variety of strange computer-game noises and simple words and to specify which he wants to use in a given instructional setting.

It should be relatively simple to develop a software kit which allows the designer to specify noises he thinks he might want in the game he is creating. At the time the game program is compiled, if no further specification for a noise like "explode" or "pop" has been given, the system could offer a menu of sound types for sampling and ask which one to use.

A similar capability ought to exist for visual effects, though here the task can get more complex. Nonetheless, it should be possible for an author to ask for a visual explosion at a particular pair of coordinates, for an object on the screen on change trajectory, etc. At a very simple level, this is possible with a very primitive microcomputer, such as the TI 99/4, when certain forms of display control circuitry are included.*2 It would also be useful, though a bit more complex to expand the graphics resources discussed above to include some level of animation (at least simple changes over short time periods).

*2 I refer to the "sprites" that are available with TI LOGO, and to other facilities on various computers that have separate display controller hardware.

IV.A.3.b The Hall Of Fame

... motivational device that can be seen in game arcades (though it probably started in instructional computer uses, such as PLATO) is the "Hall of Fame." In its simplest form, the hall of fame is simply a student-accessible record of the best performance recorded thus far. Hall of fame software should be independent of the basic software structure for the game itself. The game control module should make the results of each game available to one or more other modules that evaluate the performance and decide whether to add it to a list of best performances. Neither the writer of hall-of-fame software nor the designer of a specific game should have to worry about too many details of compatibility between those two modules.

The primary use of halls of fame seems to be in establishing goal information for game players. While some players may wish to become famous, it is striking that players often use a nom de guerre in recording their record-breaking performances in a hall of fame. Also consistent with the notion that access to goal setting and game shaping information is of great importance to student game players is the success of more general "libraries" of information about interesting student performances.

Of course, there is a paucity of research on the social comparison issues involved here, and it would seem useful to have some that was conducted specifically within the computer-based instruction environment. If it is possible to sponsor fundamental research of this sort while insuring that it is done with a strong mandate to carry the result to the computer-based instruction arena expeditiously, this might be an important item for a national research agenda.

IV.A.3.c Motivator Libraries

One of the important aspects of computer-oriented work settings is the sense of community that can develop among system users who have a common set of needs. In many systems, the electronic mail and bulletin board*3 capabilities are the most frequently used resources, and the usage is primarily nonfrivolous. Problems that might have required weeks or months to solve can sometimes be handled within hours by announcing the problem on a bulletin board and receiving mail from colleagues with suggestions. Any system user who comes up with an interesting idea that he knows will be helpful to others has a socially acceptable medium for announcing it.

*3 A few definitions: A mail system is a method for sending a message from one computer user to another, with automatic notification of the addressee of incoming mail (by system broadcast, login message, etc.). A bulletin board system is one that allows computer users to add notices to a file that any other user can access. Useful options in such systems include key-word indexed directories of current postings, automatic resources for removing old messages, and even automatic notification of a user when messages of a class in which he is interested are posted. A library is a long-term bulletin board with enhanced screening and directory capabilities.

Experience in the PLATO project, among other places, has shown that communities of students also can make good use of library and inter-student communication resources. In a sense, this is an extension of the hall of fame concept, since many of the ideas stored or announced are "record-breaking" performances. However, more than this motivation function is served. The presence of user libraries, bulletin board, and mail facilities in a computer system for instruction provides a potentially important form of computer socialization for the students. They learn that their ideas may be of use to others and that others may have solutions to problems they find difficult. Just as important, they get experience in the social aspects of information sharing.

It is a major design chore to develop the background environment for software authors and for student users of instructional software. Market factors will tend to make it hard for any one business to take on more support design work than is needed to bring their own products to market. Thus, without some collective activity aimed at deciding which tools are needed and then building them, we will end up with many good systems that are incomplete and incompatible. This will greatly multiply software costs and cut the value of individual product efforts.

IV.A.3.d Student Designed Games

While I have already mentioned student tailoring of games, the more powerful machines of the future will permit even more dramatic possibilities. Students should eventually be able to build games from scratch, with the computer intervening to assure that the games satisfy some instructional goals. Systems or <u>kits</u> (in the sense of Goldberg, 1979) for student-created games will require careful design. The problem is to allow the student to freely invent variations on a game while constraining the choices to exactly those that will provide a specific form of practice. Further, the constraints should not be too visible to the student and should not be imposed in too post hoc a manner--that is, the student should never be in the position of having specified a game only to be told, after doing all the work, that the game was unacceptable.

It is possible to write such game kits in any environment. But, it would be especially pleasant to build them in an environment that overtly specified the objects that were to be involved in a game. In such a situation, an advance constraint could be that the object could only be accessed through performance of the to-be-practiced skill. Clearly, the need for student libraries will be particularly acute if students are able to design their own games.

Perhaps the possibilities I envision can better be understood via an example. Suppose we wanted to allow students to build their choice of a variety of board games that were more or less like Monopoly. That is, they would have a board (a region on a screen) on which could be placed a game track. The student might be able to specify the structure of such a track by either drawing it or describing it (e.g., a square with 12 spaces on a side, the set of interconnected cells sketched with a light pen, etc.). It would then be necessary to provide some sort of label for each cell (square).

At this point, the basis for a finite state machine exists, where each square is a state. Many games have a move structure of the following sort: when it is your move, you (a) roll the dice, (b) move forward the number of squares indicated, and (c) possibly execute some process to find out if something else will happen. The system should be able to move a piece forward as a function of a dice roll, though the student may want to change the nature of the dice, spinner, or other move generator. What is more important is to provide a means of allowing the students to specify what the consequence of landing on any given square might be. It is here that attention to the practice goals of the game needs to be considered.

Within limited game types, it should be possible for the system to take the student's specifications and modestly alter them to maximize practice. For example, the text a student needs to read in order to know what to do at a given point could contain target vocabulary, a problem that must be worked before points can accumulate at a given square, etc. Alternatively, the student could be given a standardized frame to edit. For example, the student might want a treasure clue to be revealed at a given square. He could request this, leaving it to the system to "encode" the clue. Someone landing on the square in question would then have to break the code to get the clue. Student-modifiable games are a bit exotic for present-day instructional systems, but should be quite feasible in the future.

Game development tools, like those for other computer-based instructional procedures, should encourage highly modular design, simple access of new modules to the communications between existing modules, and explicitly specified and managed layering of the software being built. Such a resource will encourage an approach in which the author builds a prototype game, shapes it by empirical trial into a successful instructional component, and then opens it up to the student by adding options for tailoring personal versions. This may require research efforts aimed at further developing languages such as LOGO for this purpose.

IV.B Tutorial And Coaching Systems

Tutorial and coaching systems are those in which some sort of advisory or hint giver is superimposed on top of some other activity, such as a game, simulation environment, or programming environment (e.g., LOGO or Smalltalk). Such systems, in their more sophisticated forms, are best represented as a hierarchy, in which a tutor component "watches" the interaction between a student and the rest of the system, deciding when and how to intervene in that interaction. They pose a somewhat different set of requirements for authoring environments.

Of course, there are coaching systems that are much less complex, in which any sense of hints as responses to the pattern of a man-machine interaction is at best implicit. For example, the TUTOR language for PLATO, even in the late 60's (Avner & Tenczar, 1969) contained a HELP command that allowed an instructional designer to specify a piece of instructional material that a student would see if he asked for help or made certain specific errors. Such a "canned hint" capability is not the constraining factor in designing instructional systems, since it involves nothing but an expansion of the range of responses a given frame is prepared to evaluate and act upon.

Intelligent coaching systems, on the other hand, represent a major new level of complexity in computer-based instruction. Rather than being explicitly specified, sequential (or almost sequential) programs, they involve

> "interacting active procedural elements or ACTORS. ... The crucial issue then becomes the design of the sociology of ACTORS, that is, the communication and control strategies used to organize the efforts of the independent ACTORS" (Brown, Burton, Miller, deKleer, Purcell, Hausman, & Bobrow, 1975).

In such a system, the mainline interaction between the student and a game or other learning environment depends upon only one, or at least only some, of the independent procedural components. The tutor or coaching system also involves different components. Any authoring environment for systems of this type must allow for the clean, efficient, explicit specification of multi-component structures. It also must bridge the gap between multi-component systems in the author's mind and substantially simpler hardware in the student's classroom.

In this section, we review the requirements of likely future tutorial and coaching systems. A good review of issues highly related to this section can be found in Clancey, Bennett, & Cohen (1979). In that review, other architectures are proposed in addition to the one advanced below. However, I believe there are a set of common issues that will arise for any system with interacting but largely independent procedures and that such systems will be required for intelligent tutoring and coaching to take place.

The requirements for coaching and tutorial systems are discussed below in the context of the WEST system (Burton & Brown, 1979). That system provides tutorial levels of hints to a student playing a computer game called "How the West was Won" (Dugdale & Kibbie, 1977), which is a variant of Chutes and Ladders that provides drill and practice in arithmetic for elementary school students. In it, the student is given three numbers on each move (they are generated by three "spinner" displays on the screen). The student is allowed to combine the numbers into an arithmetic expression of his choice. The value of the expression determines the number of squares he is moved on the game board. There are several levels at which the game can be played.

First, one can always try for the largest number. Later, one can begin aiming for specific numbers that will be more advantageous because they land on a "chute" that permits a shortcut or because they land on a square occupied by an opponent, who must then move back some distance.

In order to provide tutorial hints to a student, the system needs to know what the student is doing (his move pattern), what the optimal moves are, and what to do to improve the student's current performances. In WEST, the task is split into two parts, diagnostic modeling and tutorial decision-making.

IV.B.1

Diagnosis of the student's current level of skill and performance is done by comparing the output of two system components, the student modeler and an expert modeler. The student modeler outputs a canonical statement of the student's recent moves. This includes the current move and the underlying skills that gave rise to it. The expert modeler similarly provides information about the <u>best</u> current move and the underlying skills that would give rise to that. The two are compared, and the result is a differential model in which information relevant to specific tutoring <u>issues</u> is provided. In the case of WEST, the types of issues are (a) the rules for composing arithmetic expressions, (b) the rules, options, and strategies for playing the game, and (c) general principles of game playing.

Of course, the issues involved in different instructional environments will vary, but the system architecture of WEST is a good example with considerable generality. The system must have several personalities, including the game player that plays the game with the student, the student modeler that watches student performance and builds a model of the student's skill, the expert modeler that describes the components of expertise relevant to the current situation, and the differential modeler that compares the expert and student models. Another major personality is the tutor, described briefly in the next section.

IV.B.2 Tutoring Strategies

There are various tutoring strategies in use in current intelligent computer-based instruction. They all have the property that they identify principles (knowledge structures) that the student does not know and then use an implicit model of learning to decide which principle to teach next and how to teach it. Further, they need mechanisms to deal with the lack of currency and completeness in the student model. Thus, they involve rather complex intelligent activity. Any system within which instruction is to be authored must provide a programming environment that allows such complex tutoring modules to be created.

In addition, the information about correct (expert) moves, the student's behavior, and the tutoring agenda needs to be represented explicitly enough to permit the student to ask questions and to constrain the tutoring process, at least in part. That is, the student should be able to respond to a suggested move with the question, "What's wrong with the move I made?" Thus, we see the need for multiple tutor roles, too. The tutor is sometimes a tactician, sometimes a strategist, and sometimes a conversationalist/advisor.

IV.B.3 Motivational Issues

Some tutoring principles may have such generality that they should be operationalized as a kit (or module) that can be added to any hinting/tutoring system. A major requirement is that other aspects of the system design should not depend upon whether the kit is in place or not. Clearly, there are also general principles of tutoring that are domain-independent, or mostly so. Consider the principles enunciated recently by John Seely Brown (quoted verbatim from Malone & Levin, 1981):

(1) Before giving advice, be sure the Issue used is one in which the student is weak.
(2) When illustrating an Issue, only use an Example (an alternate move) in which the result or outcome of that move is dramatically superior to the move made by the student.
(3) If a student is about to lose, interrupt and tutor him only with moves that will keep him from losing.
(4) Do not tutor on two consecutive moves, no matter what.
(5) Do not tutor before the student has a chance to discover the game for himself.
(6) Do not provide only criticism when the Tutor breaks in! If the student makes an exceptional move, identify why it is good and congratulate him.
(7) After giving advice to the student, offer him a chance to retake his turn, but do not force him to.
(8) Always have the Computer Expert play an optimal game.
(9) If the student asks for help, provide several levels of hints.
(10) If the student is losing consistently, adjust the level of play.

(11) If the student makes a potentially careless error, be forgiving. But provide explicit commentary in case it was not just careless.

A number of issues for the design of authoring environments are brought out by Brown's suggestions. Consider Suggestion 10, which concerned adjusting the level of game the computer is playing against the student. This principle involves keeping track of the progress of the student's game, which is something the student model will probably be doing, at least implicitly. The action to be taken, though, is to modify the game-player module, not to intervene with a hint. Suggestion 7 involves both hint giving and modifying the game player (at least minimally). Suggestion 3 involves supervising the tutor in light of information that must come from the expert model.

What is apparent is that a "motivation principles kit," surely something desirable, must be able to observe the activity of various components and intervene. It would be ideal if such kits could be added to any particular system without regard to the specific content of the system, knowing only that it was created in an authoring environment that supports this class of kits. Much more important, we need to greatly extend the research that Brown and others have begun. We need a theory of tutoring, and that is a major cognitive psychological research task. It is justified as a priority research agenda item by the sudden emergence of tutoring as something that we can afford to do much more than in the past--if we know how to do it well and substantially by machine.

IV.B.4 Conversational Capabilities

An obvious area of concern for future authoring environments is that they provide tools for interacting with the student in a relatively natural way. A complete natural language generator is beyond current technology and certainly beyond the scope of the machines likely to be in schools in the next few years. Nonetheless, even constrained text generators that are imperfect will be of some use. The tutor needs to be able to interact with the child! The authoring environment used by computer-based instruction designers should offer a variety of partial language parsers and sentence generators that can be used as tools by the instructional systems author. A standardized way of installing a parser or text generator as the one to be used in a particular instructional product will be very helpful, as will a standardized means for requesting natural language output and the parsing of new input.

IV.B.5 Summary Of Tutoring System Research Needs

I can summarize the foregoing discussion of tutoring and hinting by suggesting several areas in which research might be needed:

- The hinting/tutoring process requires a style of system design that emphasizes multiple independent modules that share in common some knowledge and also knowledge of each other's activity. The programming environments needed to support such efforts are starting to become available, but there is need for sufficient support of prototype development to produce clear principles for designing such systems.

- Intelligent tutoring systems represent state-of-the-art artificial intelligence and require authoring environments that do not restrict the range of programming resources the author uses. The trick will be to provide this flexibility while maintaining (or laying the groundwork for) maximal portability of systems from one running environment to another. Research will be needed to clarify <u>what</u> should be portable: every program, certain run-time environments, cross-compilers, interpreters, ...

- A theory of tutoring must be developed in the context of intelligent computer-based instruction. This is perhaps the single most important long-term research need if the power of computers is to be adequately exploited.

- Research is needed to improve the natural language communications resources available for instructional uses. If we know more about the student's specific knowledge lacks, or if we know about aptitude weaknesses, we need to be able to tailor how we talk to the student in the course of his learning. This is true whether the <u>we</u> of the last sentence is human or artificial.

IV.C Laboratories And Exploratory Environments

I next consider open-ended laboratory environments in which the student is able to do a wide variety of activities. Such environments can be monitored by tutors, like any other. Their crucial property should be that almost any reasonable probable pattern of behavior by a student in using the environment should be a useful learning experience. Open-ended environments can be used in two ways. One approach is to let the student decide how to use the environment, perhaps providing some hints along the way. A somewhat different approach is to treat the environment as a laboratory in which specific exercises are to be carried out. These are extreme positions on a continuum of uses.

IV.C.1 Computing Languages For Children: The General Lab

At least one general computational environment ought to be available on any instructional system. Three primary candidates for such environments are BASIC, LOGO, and Smalltalk. I briefly discuss each of these possibilities in turn, hoping to clarify the issues yet to be faced in designing computer languages for children.

It is fashionable to look down at BASIC, and I tend to follow this particular fashion myself. Nonetheless, it is important to realize that just about every microcomputer in a school today has a BASIC interpreter. Thus, for example, a book of computer literacy lessons or lab exercises for algebra that called for BASIC programs to be written would have wide generality. Further, some of the properties of BASIC were specifically designed to help facilitate use of computers by people with no computer background.

The most important property of BASIC is that it minimizes the need to understand the traditional series of events involved in writing and executing a program: editing, compiling, loading/linking operations, and actual execution. What could be simpler than typing in steps of a program in any order and then saying RUN. Corrections require no knowledge of editors or editing commands.*5 There are no compiler and linker conventions to learn about. The syntax of BASIC is straightforward. It ought to be the ideal playground and laboratory environment for the computer.

It is not. The reasons have more to do with advances in what resources are routinely available on a computer than in any lack of design skill in the people who put BASIC together in the first place (Kemeny and others). Today, even the smallest microcomputers have more memory and faster performance than the systems for which BASIC was written. Also, instead of printing terminals that can only output 10 characters per second, which were the tools in the first BASIC laboratories for students, we now have video display systems that can be updated 12 to 96 times faster than the teletype. As a result, traditional BASIC systems have the following shortcomings relative to the state-of-the-art:

1. They require the user to keep in mind, or on paper, the entire program. The user can only edit by naming line numbers. Thus, the structure of the language reflects the trivial task of issuing commands rather than the more basic task of planning how a problem is to be solved.

2. Because the only mode of editing is to retype the whole line, editing is unnecessarily inefficient, requiring more key strokes than necessary, perhaps by a factor of 10 to 30 (cf. Card, Moran, & Newell, 1980).

3. Because BASIC was written to be an interpreted language on slow systems, it has only limited program structuring capabilities. None of the conventions of current programming practice, mainly involving highly modular, hierarchical design, can be explicit in BASIC programs.

*5 A naive user might find the 110+ editor commands of the editor I used to write this paper a significant barrier to rapid functional use of the machine, I suppose.

4. BASIC was written at a time when computers primarily handled numbers and perhaps character strings. There is a lack of richness in the data types available. In particular, list structures are not available.

5. No recursion is allowed in BASIC.

6. No explicit characterization of independent, interacting "actors" is possible with BASIC.

7. No graphics support is available in BASIC.

For most of the complaints just listed, there will be challenges that some newer microcomputer systems provide the resource in question. This is partly true. However, the problem is standardization. The standardization of BASIC is largely restricted to the components it had in its early years. Screen-oriented editing, graphics commands, etc., are not standardized. Hence, real investments are required to build software that runs on multiple systems. Usually, the efforts are not made. Perusal of any personal computer magazine will reveal that software advertisements list BASIC programs according to the systems under which they will run. Further, problems such as lack of support for modular design are seldom really addressed at all. Thus, BASIC seems inappropriate for instructional use.

One problem is that much grass roots software development for education is in BASIC. Hundreds of teachers are writing BASIC programs for their classrooms today. There has been an enormous investment of effort in BASIC by the very people otherwise most likely to be receptive to newer systems. Also, we look at BASIC as an example of the problems that arise when efforts after standardization are delayed too long. Just as with other "standard" languages like FORTRAN and COBOL, BASIC survives because of the investment already made in it. To move to another language, retaining and program conversion on an enormous scale will be required.

This suggests that a significant effort should be made to develop prototype languages for children that are better than BASIC and to understand why they are better. The next two languages are of that sort, especially LOGO. They are important, but yet incomplete steps. So much of the recent emphasis in LOGO development efforts, for example, has been on fitting the language into impoverished machines. A new effort will be needed to specify what a complete implementation ought to have and to test the validity of such specifications.

IV.C.1.b LOGO

An interesting contrast to BASIC is provided by LOGO. LOGO has also been designed as an easy to learn language (it also has a specific orientation toward children's learning that is quite different than those that motivated the BASIC originators; see Papert, 1980). It was not originally meant as a standardized language. Perhaps the best overview of its design philosophy is offered by Papert himself:

LOGO is the name of a philosophy of education in a growing family of languages that goes with it. Characteristic features of the LOGO family of languages include procedural definitions with local variables to permit recursion. Thus, in LOGO it is possible to define new commands and functions which can then be used exactly like the primitive ones. LOGO is an interpretive language. This means that it can be used interactively. The modern LOGO systems have full list structure, that is to say, the language can operate on lists whose elements can themselves be lists, lists of lists, and so forth.

Some versions have elements of parallel processing and of message passing in order to facilitate graphics programming. An example of a powerful use of list structure is the representation of LOGO procedures themselves as lists of lists so that LOGO procedures can construct, modify, and run other LOGO procedures. Thus LOGO is not a "toy," a language only for children.

...It should be carefully remembered that LOGO is never conceived as a final product or offered as "the definitive language." Here I present it as a sample to show that something better is possible. [p. 217]

Indeed, several different implementations exist already for microcomputers (e.g., for the Texas Instruments 99/4, the Apple II Plus, and the Terak 8510/a). All of them will be of value in instruction. The differences, however, may create compatibility problems. For example, the Texas Instruments product implements some graphics object capability in hardware. Thus LOGO programs can run animations by passing messages to "sprites" that run in parallel to the LOGO program. On the other hand, TI LOGO does not have real (noninteger) arithmetic. Also, it does not have the rich list structure capabilities Papert described. There will therefore be many programs that cannot be transported from one system to the other. However, various recent books (Abelson, 1982; Abelson & diSessa, 1981; Papert, 1980) include enough exercises that can be implemented across all versions, that it seems appropriate to speak of a core LOGO that ought to be available to an instructional systems author to insert in specific systems.

This paper is not a study of the uses of systems but rather of their requirements. For that reason, I have resisted providing illustrations of many LOGO features. However, two related aspects of the LOGO project's work merit brief mention. First, there is the turtle. In the early years of the LOGO project, there was actually a physical turtle that could be moved around by LOGO command. Today, the "turtle" is a dot on the screen that can leave a track behind it. The turtle is an important way to make the function of a program concrete and will no doubt continue to be a major resource for teaching children to use computers.

A very different tour de force, but one involving the "turtle," has recently been completed by Abelson and diSessa (1981). They have built a geometry using the turtle's capabilities as the primitive operations. This procedural geometry is powerful enough to provide an underpinning for both everyday high school geometry and more sophisticated concepts, including the geometric notions underlying relativity theory. Presumably, a basis for instructional systems that use the turtle to teach aspects of mathematics that involve spatial concepts has been created by this work. This again illustrates the importance for future instructional system designers of being able to embed something with the power of LOGO into their systems. Such power will need to be fully incorporated in such a way that tutor components can interact with the student as programmer just as they interact with the student as game-player.

There is another way of thinking about LOGO. In essence, LOGO is a simplified form of LISP. LISP is the language that has emerged as the standard in artificial intelligence applications. This is because it provides an understandable bridge between our most fundamental knowledge of what computation is about and the kinds of problems and knowledge structures that constitute complex intelligent activity. Thus, the future of LISP standardization and development ought to drive future LOGO development. What is needed in addition is consideration of the course of cognitive development and of the school curriculum in order to specify the aspects of LISP that LOGO should include. The final step of developing simplified syntax for those needed capabilities is the easiest part of the chore.

Parenthetically, I might add that a recent meeting Mark Miller of Computer*Thought, Inc. suggested that LOGO might also be the authoring language used by instructional designers. By that, I suspect he meant that a subset of the best new LISP environments might, with simplified syntax, be just the right language for authoring. There remains the problem of providing appropriate canned tools within whichever language is chosen.

IV.C.1.c Smalltalk

Another language to be considered is Smalltalk. Actually, Smalltalk is presently found in research laboratories, most notably XEROX Palo Alto Research Center. However, the Learning Research Group at XEROX PARC has used Smalltalk for a variety of instructional ventures. Forthcoming books (Goldberg, Robson, & Ingalls, forthcoming-a,b) will provide more authoritative documentation. However, quite a bit has already been published that deals with Smalltalk (Althoff, 1981; Borning, 1979; Bowman & Flegal, 1981; Deutsch, 1981; Goldberg, 1979, 1981; Goldberg & Robson, 1981; Goldberg & Ross, 1981; Gould & Finzer, 1981; Ingalls, 1981a,b; Kaehler, 1981; Krasner, 1981; Reenskaug, 1981; Robson, 1981; Tesler, 1981; XEROX Learning Research Group, 1981), so it is reasonable to begin a public discussion of its features and the implications it has for computer-based instruction.

LOGO was originally specified as a language for teaching children about computers (or allowing them to learn about computers). While such possibilities ran through the minds of Smalltalk inventors, the emerging concern has been with Smalltalk as a modern, <u>tailorable</u> personal computer environment, in which the tailoring might be done partly by the end user and partly by special systems developers. Like LOGO, it treats procedures defined by the user as being of equal status (and invoked with the same syntax) as the commands that are built into the system at the "factory." The resulting system seen by a student might be extremely specific, as in work done by Gould & Finzer (1981) with junior college students in a remedial algebra class. Or, it might be rather unconstrained but with specialized tools, as in a kit for graphic artists (Bowman & Flegal, 1981). Or, it might be completely general (as described in Tesler, 1981).

One way to get a quick sense of the nature of Smalltalk is to consider the design principles that David Ingalls (1981a), one of its designers, has stated for it, from which I quote (the principles are interspersed throughout his article, separated by explanatory text which I omit).

> Personal Mastery: If a system is to serve the creative spirit, it must be entirely comprehensible to a single individual.
>
> Good Design: A system should be built with a minimum set of unchangeable parts; those parts should be as general as possible; and all parts of the system should be held in a uniform framework.
>
> Scope: The design of a language for using computers must deal with internal models, external media, and the interaction between these in both the human and the computer.
>
> Objects: A computer language should support the concept of "object" and provide a uniform means for referring to the objects in its universe.
>
> Storage Management: To be truly "object-oriented," a computer system must provide automatic storage management [so the user doesn't have to program memory considerations into specific combinations of objects].
>
> Messages: Computing should be viewed as an intrinsic capability of objects that can be uniformly invoked by sending messages.
>
> Uniform Metaphor: A language should be designed around a powerful metaphor that can be uniformly applied in all areas.
>
> Modularity: No component in a complex system should depend on the internal details of any other component.
>
> Classification: A language must provide a means for classifying similar objects, and for adding new classes of objects on equal footing with the kernel classes of the system.
>
> Polymorphism: A program should specify only the behavior of objects, not their representation. [That is, no request to an object should depend upon how the object does the required task, only upon what is done.]
>
> Factoring: Each independent component in a system should appear in only one place.
>
> Leverage: When a system is well factored, great leverage is available to users and implementers alike. [That is, they can concentrate their attention on the specific new ideas they are adding to an existing base.]
>
> Virtual Machine: A virtual machine specification establishes

the framework for the application of technology [by specifying exactly the machine-dependent core of the system. Only that core needs to be reimplemented on each new machine.]
Reactive Principle: Every component accessible to the user should be able to present itself in a meaningful way for observation and manipulation.
Operating System: An operating system is a collection of things that don't fit into a language [and/or don't follow the reactive principle]. There shouldn't be one.
Natural Selection: Languages and systems that are of sound design will persist, to be supplanted only by better ones.

The best way to get a sense of the value of Smalltalk is to look at descriptions of interactions with it. Tesler (1981) has provided an extensive description to which the reader is referred. One way to contrast Smalltalk with other programming environments is to examine the ways in which it exhibits its various personnae to the user. In ordinary systems, one can only talk to the computer in one mode at a time. That is, the computer only puts on one personna at a time. When a particular personna is active, no other personnae have any preserved context information that would allow switching back and forth between them.

This means that the same string of characters typed on a keyboard can have different meaning at different times. For example, a given string can be the name of a program to run, an instruction to the program, or data on which the program should operate. Also, it is generally difficult or impossible to step out of one frame of reference, do something else, and then return to that frame without loss of some context information. One cannot, for example, stop examining the output of a program, look instead at a listing of it, or at the data it is processing, and then return to the midst of the program's execution. Smalltalk (along with recent languages for systems with "window" hardware) is set up to permit this. Also, Smalltalk depends heavily on menus as the means for avoiding the multiple mode problem. At any given point one chooses one of the available options from a menu rather than typing something which may or may not reflect the choice desired.

Because Smalltalk has been designed to be used in an exploratory programming mode, it is particularly useful for certain forms of student exploratory activity. Thus we consider it alongside LOGO. It is not, as it stands, very accessible to young children (Goldberg & Ross, 1981), though with added primitives it could become more useful. Its utility lies in the following properties, according to one of its designers (Tesler, 1981, p. 98-100).

1. The language is more concise than most, so less time is spent at the keyboard.

2. The text editor is simple, modeless, and requires a minimum of keystrokes.

3. The user can move around among programming, compiling, testing, and debugging activities with the push of a button.

4. Any desired information about the program or its execution is accessible in seconds with minimum effort.

5. The compiler can translate and relink a single change into the environment in a few seconds (on XEROX's powerful machines), so the time usually wasted waiting for recompilation after a small program modification is avoided. (This may not be true on smaller machines to which Smalltalk is exported.)

One is left with great admiration and covetousness after examining Smalltalk. However, it is important to note that many people have difficulty learning to program from scratch in the language even though use of some of the resource kits that have been written for it is quite easy. In essence, while LOGO provides us with a sense of how a language can be simplified without losing power, Smalltalk provides a sense of some of the tools that ought to be included in future language systems. Research is needed to better specify which tools are needed and perhaps also the best approaches to the simplification process.

IV.C.2 Replacing "Wet" Labs

An extremely important form of computer-based education is the virtual laboratory that provides a concrete set of experiences to enhance "book learning." The traditional type of science lab can be expanded into the computer realm. Simply making lab experience less costly is an important contribution of computer-based labs, but they do much more, or at least they can. I shall describe two laboratory programs that, between them, illustrate some of the possibilities.

The first is a product of colleagues, a mechanics simulation developed with NSF and NIE sponsorship by Audrey Champagne, Leo Klopfer, James Fox, and Karl Scheuerman. One of their modules simulates the Atwood machine, which consists of a block on a table which is connected by a rope to a bucket of sand. The bucket hangs over the edge of the table, with the rope running from the bucket, through a pulley, to the block. The bucket is "held" until the simulation starts, then it is released and falls to the floor, pulling the block. Such a demonstration is not too complicated, and it could easily and cheaply be done in class. However, the computer allows things that are not otherwise possible.

For example, there have been a number of demonstrations that students, even after a physics course, often do not understand the relationships between forces and object movements. While Newton taught us that force = mass x acceleration, students often associate a force with velocity instead of acceleration. It would be nice if we could show students the world as they think it works and compare that to the world the way it really works. This is impossible with real demonstrations but straightforward with computer animation. We simply make the block move at uniform speed while the bucket is falling if we want a naive view and let it accelerate as the bucket falls if we want a Newtonian view.

Of course, the problem is deeper; students often fail to perceive acceleration when they see it. To overcome this, Champagne et al. used several techniques. In the animation, the block clicked every time it moved a unit distance; faster clicks meant faster movement, and the sound change was more perceptible. Graphs were also provided of displacement versus time. In addition, a trace could be left by the block on the table top every unit time period; more distance between traces means faster movement. All of these methods were used with good effect. All represent improvements over the "real" demonstration. All operate well even if the teacher is a bit unsure of the relevant principles himself.

A second example is the ARITHMEKIT being developed by Brown, Burton, and others at XEROX Palo Alto Research Center. This laboratory environment is still in preliminary form. It allows students to perform numerical computations, such as addition and subtraction and to see parallel illustrations with Dienes blocks that correspond to their numerical manipulations. Like the best games, though, it has multiple levels of function. For example, students can use advanced graphics facilities to assemble a "machine" that does adding or subtracting. They can connect the various digit locations in an arithmetic problem together with adders, carry devices, one-column subtracters, etc. This allows a more elaborated level of understanding of the meaning of adding and subtracting. Finally, though I haven't seen evidence of it yet, one can assume from their past work that the next level of complexity will be "machine"-building tasks for the students (and perhaps their teachers) in which they attempt to build working models that match the mistakes of other children.

Again, the world of graphics that can be manipulated with a joystick or "mouse" provides fantastic opportunities for exploratory environments, whether we think of these environments as laboratories or as game-like worlds. However, the design of such environments requires solution of a number of fundamental problems of cognitive instructional theory. It is no accident that the work so far has been concentrated in a very small number of research centers that happen to have concentrations of computer science, cognitive psychology, and instructional design specialists in close proximity. Even in these few locations, the work proceeds at a very limited pace. The combination of equipment needs, other financial support requirements, and the fact that existing funding is generally tied to somewhat tangential issues has hampered the rate of advances in this area.

IV.D New Types Of Needs In Computer-based Instruction

There are a few additional considerations that arise simply because intelligent computer-based instruction is so novel.

- There is the need to teach teachers how to use new systems and what those systems can accomplish.
- There is the need to convince a skeptical public, including teachers, that some of the novel formats being proposed are instructionally sound. After all, many people have little use for computer-based games at all, much less in the classroom.

o Because of the more complex set of objectives for some recent computer-based instruction, there is probably need for intelligent monitoring of student-program interaction to support debugging and refinement of instructional strategies and tactics.

Each of these is discussed below.

IV.D.1 Teaching The Teacher

Intelligent computer-based instruction is a means for doing what has always gone on in instruction. It is also a means for providing instruction of a sort not previously possible. Each of these capabilities poses special problems for the teacher.

In the case of systems that do what has always been done, the teacher still faces a somewhat different task, if for no other reason than the individualization of instruction that the computer permits. This puts record keeping stresses on the teacher as well as the burden of learning how to operate the computer system. Often, the burden is even greater. In current school systems that face declining enrollments coincident with shortages of teachers in certain subject matter areas, it is not unusual for teachers to be assigned classes in areas for which they do not have substantial subject- matter training. Often, a teacher in that position is perfectly able to follow the textbook and teacher manual but may not have the depth and automation of subject-matter knowledge needed to design individual programs of instruction for different student needs. Thus, there will be some need for the teacher to receive an explanation and interpretation of the progress trajectories of various students through the curriculum.*6

When the computer is used to expand the instructional offerings of a school system, the need to explain to the teacher what is going on and what the student is learning is even more acute. Yet, the promise of computer-based instruction of this type is particularly high. It is hoped that gifted children will be able to take high school courses in elementary school, sailors will be able to study domains at sea even if no human expert is available, etc. Such a facility would be quite useful. It will still have to be monitored by a human who will want to know what the student is being taught. That human also ought to be able to get tailored explanations of the principles being taught so that he/she is in a position to answer questions, advise on future courses of instruction and otherwise be the human professional who leads the instructional process.

There is another aspect to this notion of teaching the teacher. By being in computer-intensive environments, our children will learn how to use and get

*6 This need is not meant to reflect negatively on teacher skill. Rather, it arises any time the computer is used as an expert to extend the capabilities of a human. My realization of the importance of this requirement comes from watching very expert physicians try to convince themselves that diagnoses provided by the MYCIN (Shortliffe, 1976) were reasonable.

along with intelligent artifacts. This will be both fun and practically useful. Certainly, we their parents, teachers, and leaders should not be left out of all this. It may be worthwhile, even essential, to have specific prototype efforts that aim at integrating teacher training into instructional systems.

IV.D.2 Convincing The Skeptic

A final teacher need is shared with parents, school committee members, and the lay public. This is the need to be convinced that activities on the computer that look like idle fun are in fact instructionally important. Much of the current efforts of the best computer-based instruction authors is going into the design of instructional games. Ideally, these games should have relevant motivational devices. That is, the student should come to be motivated by the acquisition of the target skills. However, in the early stages of learning a skill, the nature of the skill is not well enough understood by the student, and other motivational schemes may be necessary. In either case, it may not be immediately apparent to an outsider watching a game that important schooling is taking place.

I believe that many instructional game systems will require an intelligent commentator that can provide a skeptic with an account of the progress of a game-playing child in mastering skills via game playing and with an analysis of how a particular game teaches a particular skill. This need is similar to that of the teacher as described above, but it will require focus on a different set of concerns and the assumption of a lower level of specific teaching knowledge in the person requesting this information. Laymen will have to be able to ask questions about the course of an individual student's instruction and about the instructional strategies of the system in general.*7

It is likely that separate program objects (semi-independent software modules) will be the most appropriate vehicles for providing this type of information. Such objects will have to be able to access the information created and used by the objects that actually provide the student interaction and hinting. They should hopefully be as independent as possible of specific subject matter areas, to facilitate their transfer to new instructional systems. It is unlikely that market forces will produce such a capability when there are cheaper but more artificial ways of calming down parent concerns and of selling instructional products. However, an important governmental role is in raising the sights and aspirations of the populace, something a well-publicized prototype venture in this area might do.

IV.D.3 Intelligent Monitoring And Protocol Gathering

One of the reasons that programmed instruction has had only modest impact on

*7 This type of resource will also be of use in providing support for the individualized educational plans that are mandated for gifted and disabled children.

schooling is that instructional systems designers rapidly abandoned their initial ties to the psychological research that spawned the field. As a result, a wonderful opportunity for this area of application to refresh and be refreshed by instructional researchers was limited. We should give careful consideration to possibilities for making new computer-based instruction efforts more amenable to development in concert with a continuous research process. The system developer will want to study patterns of interaction to determine whether the system is doing what he/she wants it to do. The researcher would like to gather protocols of the instructional process. In both cases, several constraints apply. First, the terminal interaction trace is probably not sufficient. It may be difficult-to-digest form (if substantial graphics are involved and timing information is also wanted). More important, information about the decisions and assumptions of the system regarding the student's skill level and the appropriate tutoring and lesson choices will be as necessary as the raw interaction protocols. Given the amount of information involved, there will be need to organize and report it in summary form if it is to be seriously used on a routine basis.

This suggests the need for a "research assistant" object that collects protocols of both the man-machine interaction and the underlying "thinking activity" within the computer that was relevant to that interaction. Like any good assistant, such a mechanism will be more valuable if it can prepare summaries of the data so the user does not have to wade through piles of information on multiple time tracks by hand. Kits should be conceived so that "research assistant" modules can be built into an instructional system as it is being designed. Such kits are not likely to come from commercial sources.

V.0 ISSUES OF ARTISTRY AND CRAFTSMANSHIP

So far, I have discussed specific instructional paradigms and, to a lesser extent, the basic psychological issues related to them. I wish to conclude with several suggestions concerning the kind of exemplary prototypes that should be encouraged by any grant competition. My concern is specifically with issues of craftsmanship that may themselves generate research needs.

One important concern is human-machine interaction. Initially, computers delivered instruction via teletype terminals. Communication was too slow, too verbal, and too dependent on typing skills. Today, there are modest improvements in the personal machines used in schools. Displays are generated more quickly, and graphics are commonly available. However, the student still inputs via a keyboard in too many cases. The touch screen, the joystick, the mouse, and other spatial input devices that can move a cursor quickly around the screen need to be exploited much more completely. Also, the underlying software to support such devices needs to be improved (e.g., many programs can use a joystick, but the joystick seems too hard to control; there are software cures for this problem). Students should be able to assemble many responses by "picking up pieces" from the screen display and rearranging them (Gertrude's Secrets and other Piestrup programs show that this can be done on an Apple, though the programs could use better joystick routines).

Fundamental constraints are created by the reliance of many small computers on commecial television sets. Color television sets have very low resolution. Perhaps 16 rows of 32 characters each can be displayed with clarity. Thus, they are inadequate for many types of displays that we will want. The low resolution results in poor character fonts in these systems' video displays (no one would read this paper if it were printed in the type style used on an Apple II, for example). An important research issue is the identification of an appropriate new standard for instructional video displays. Maybe industry will do this for us if appropriately stimulated, but the issue merits discussion in these meetings.

Even with improved graphics tools, we will need to set high standards of artistry in using them and will need to foster the development of tool kits that make it easy to design screen graphics. More generally, we will need to create authoring environments that are easy to use and that allow a designer to focus on producing a coherent functional design and not on how to cram new options into an underpowered system that lacks appropriate runtime support software.

V.A Maintainability And Extensibility

I am not an expert on operating system design, so my final comments must be taken with skepticism. It seems to me that a major longterm issue for instructional computing is software maintenance and extensibility. So far, the market forces in the personal machine world have favored treating software as a disposable product. That is, there is relatively little maintenance or consulting available, and new products generally replace older ones rather than building from them. The exceptions are in business software which tends to run on more expensive hardware configurations and tends to cost about ten times as much as instructional software. Is this the right way to go? I don't know, but I could imagine a small amount of funding being spent on economic-technological analysis and forecasting to help answer the question school people always ask me: Will I be able to build onto this system as new products appear? Right now, the answer is usually no; should it be?

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THE NEW SCIENCE EDUCATION

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A qualitatively new kind of computing machine (the 16-bit micro-computer) is coming on the market. It will be cheap enough to be bought by families, individuals and schools. It is powerful enough to do things that are totally different from the simple activities of current classroom computers. These computers completely change the possibilities for use of computers in the classroom. Furthermore, for two reasons they have a particularly great potential for impact on science education. (1) As I will discuss later, there is already relevant research that can support principled development of good science education on these machines, further research could provide an even more extensive basis for education development. (2) Education in science is particularly crucial to our ever more technological society. We cannot employ more conventional steel and assembly-line workers. We do need (in the long run) more engineers, computer-programmers, and technical support people, all of whom need knowledge of science. Thus anything we do to improve markedly our teaching of science is likely to have a large societal impact. The 16-bit micro-computer offers us a completely new opportunity.

To realize the impact of these new machines, we need to figure out how to use effectively the computational power they will make available. The purpose of this paper is first to describe the new machines and what they can do, and then to outline a research agenda aimed at discovering enough about human learning in science that we can use the power of these machines to provide qualitatively better instruction.

1. The New Machines

There is a new generation of small computers. Like their predecessors (the current 8-bit micro-computers), they will be cheap. Carnegie-Mellon University plans, within five years, to use machines costing about $7,000 each and one would expect them to be even cheaper within a few years. Unlike the current 8-bit micro-computers, however, these machines are powerful. Probably anything you are currently doing on a "big" machine you could do on one of these. You could analyze data. You could edit and prepare manuscripts with graphics and special type fonts.

Most importantly, these machines are sufficiently powerful that they can support what is called "artificial" intelligence. For the uninitiated, an artificial-intelligence computer program or "system" is a program that does things that we would ordinarily say require intelligence. For example, one existing artificial-intelligence system reads wire-service articles and constructs coherent and correct summaries (Schank, 1980; Schank & Abelson, 1977). Another diagnoses bacterial diseases, interpreting symptoms and laboratory results, identifying the most likely responsible organisms, and using these results, together with other knowledge of the patient (e.g., general health, any allergies, etc.) to prescribe appropriate treatment (Shortliffe, 1976).

The text-understanding and medical-diagnosis programs are qualitatively different from most familiar programs. Do not confuse them either with the mechanical programs that send you bank statements or with the simple routines that now support games and activities in the classroom. Indeed, the potential impact of these new machines is great enough that we clearly must be careful not to use them in stupid or harmful ways. To reflect this qualitative difference, I will use the conventional term "artificial intelligence" for modern, computationally powerful systems that do appreciably more than routinized activities. It is irrelevant whether philosophically these systems are "really" intelligent. They can do qualitatively more than any cheap machine we have ever seen.

Machines like these have a tremendous potential for impact on education. Think about teaching English, for example, and imagine having in your classroom a machine that summarizes stories (including student stories) and asks or answers questions about them. A system that understands stories is further able to parse sentences, and so this system can give students feedback on their grammar or on how difficult their sentences are to parse. Similarly, imagine senior medical students using a machine that can provide individual expert consultation to each student whenever he wants it.

As is evident from these examples, there are many artificially intelligent systems. What is new, and is the focus of this paper, is that machines capable of supporting artificial intelligence are becoming cheap. Thus your family and your school will soon buy machines that have the capability of doing tasks equivalent to consulting on medical diagnoses or summarizing newspaper stories. How can we use this power effectively to produce better education?

2. A Fantasy

To explore this question, let me share with you my fantasy, set in about 1992, of how powerful computation might contribute to university-level physics and engineering. With this fantasy, I'll describe the kind of research that could make it a reality, including both current and possible future research.

I imagine a student engaged in the primary task of science, trying to solve a problem, let us say a circuit problem. As he sits down at his computer to work, one available tool is a circuit "editor" that first allows him to construct circuit diagrams by connecting components drawn on his high-resolution graphics screen. This editor developed out of editors for computer languages (e.g., the GNOME system at Carnegie-Mellon University [Miller, 1983]). Like the earlier computer-language editors, this circuit editor views circuits hierarchically. The student can work at any level in the hierarchy, and the editor keeps track of where he is and what components may appropriately be added. If the student indicates his circuit is complete, the editor may remind him of missing pieces. The editor handles not only construction circuit diagrams, but also applying circuit principles. Thus at any level in the hierarchy the student can apply a principle like "current in equals current out", or V = IR. The editor prevents inappropriate applications, like V = IR to a battery or current in equals current out to an undefined system.

The editor is itself a powerful instructional device for several reasons. First, its hierarchical structure is based on work by Riley (1983) suggesting that circuit problems are solved most easily when they are represented as embedded part-whole structures. Additional work (Unknown, 1992) has shown that users of any sort of editor tend to adopt autonomously the strategies of that editor. Thus, for example, users of the Bell- Laboratories Writers' Workbench (Frase et al., 1981) avoid cumbersome written constructions even when they are writing without the computer-based editor (Unknown, 1992). Thus my fantasy circuit editor actually helps students to learn to use effective strategies for thinking about circuits.

Second, the circuit editor, like the early computer-language editors (Miller, 1983), drastically reduces the amount of time required to learn to use circuit principles to solve problems. For example, an editor for PL1 produced a reported decrease of 50% in the time required for students to complete the work of an introductory programming course. Subsequent research on this fascinating result (Unknown, 1992) showed the following reasons for it: (1) By keeping track of many details, the editor frees students to concentrate on and learn more effectively the important principles of programming. This result is related to earlier work (Reder & Anderson, 1980) indicating that people learn summary material better if they are not also required to study supporting details. (2) The editor prevents many silly mistakes that are enormously time consuming to correct. Even in 1982 it was almost impossible to make a syntax error while programming with the GNOME editor.

There was some initial concern that students might become dependent on the editor and more prone to silly mistakes when working without it. In fact, as shown by research cited earlier (Unknown, 1992), an editor that prevents silly mistakes is one of the most effective ways of learning to avoid them yourself. Also, of course, our view about the role of computer tools has evolved since the early 80's. All professionals now use routinely computer tools, and we don't judge their "dependency" on tools, but their scientific creativity using the best tools available.

Research on novice problem solving begun in the 70's (Larkin, McDermott, Simon, & Simon, 1980) indicates that for quantitative problems, novice solvers almost always start work with equations rather than with conceptual or "semantic" models of the situation. As expected, our fantasy student starts his problem solution by trying to write equations describing his circuit problem. Because the editor helps him to keep track of the various systems to which these equations apply, he is considerably more effective than the ordinary student of the 80's (cf., Larkin & Reif, 1979; Larkin, 1983), and actually comes very close to solving the problem. However, he is confused; some of the equations don't seem reasonable to him.

Considerable research (Unknown, 1992) has clarified and extended what good teachers have always known: it's very important that equations seem reasonable and have meaning. The reason is that without associated meaning, human beings quickly forget details and then reconstruct them incorrectly. Thus a student who doesn't understand <u>why</u> V = IR may well remember this equation as I = VR. This faulty reconstruction is related to the basic research by (Reder, 1982) suggesting that the primary form of memory is not recall, but reconstruction from related knowledge. Thus an equation learned without related knowledge is almost sure to be forgotten.

How does one help students to learn equations or algorithms with meaning? Resnick (1981) began to work out the details of how children connect the place-value subtraction algorithm to a model involving visible objects. Children acted out subtraction using Dienes blocks (Dienes, 1960), blocks that represent powers of 10 by single blocks, sticks comprising 10 single blocks, squares comprising 100 single blocks, etc. Acting out the algorithm while writing its results on paper dramatically improved the abilities of individual children to use the place-value subtraction algorithm. Subsequent work (Unknown, 1992) both verified these results with larger groups of children, and specified more clearly the crucial features of this procedure for adding meaning to a mathematical algorithm. An experimental computer-based instructional system (Brown, 1983) provides an environment in which visual blocks and sticks are strongly connected to written subtraction notation.

In the more advanced physical sciences, a series of research studies (Larkin, 1983; Chi, Feltovich, & Glaser, 1981; de Kleer & Brown, 1981; Gentner, 1980; Gentner & Gentner, 1982; Unknown, 1992) have quite completely elucidated many of the meaningful problem representations that experts use. Some of these have been programmed and are available to my fantasy student. Thus he can visually expand the wires in his circuit, and watch electrons flowing through the paths. He can deform the circuit three-dimensionally so that the height of any part of the circuit indicates its electric potential. (Preliminary work as far back as 1979 [Larkin & Reif, 1979; Larkin, 1983] suggested that these two representations greatly improved students' ability to solve simple circuit problems.) For more complex circuits, the student can see electric and magnetic field lines interacting around capacitors and inductors. More sophisticated students are likely to use more sophisticated causal models based on the work of de Kleer (1979).

Thus the student has available to him a powerful simulation system that can show him, at varying levels of detail, what is happening in any circuit he constructs. The software concepts underlying this simulation were initially developed for the STEAMER project (Williams, Hollan & Stevens, 1981) describing a nuclear steam plant and providing simulations and explanations of both global operation and detailed mechanisms of the underlying processes.

The visual effects in these simulations are impressive and important. Ongoing work by Kosslyn and his colleagues (Kosslyn, 1979; Unknown, 1992) has spelled out the exact characteristics that make visual displays most effective. Kosslyn's early work concerned effective design of charts and graphs (Kosslyn, 1979). More recently (Unknown, 1992) this work has expanded to define principles of effective visual design for a broad range of computer simulations. All of this work is based on Kosslyn's developing model of the interaction between human's internal mental imagery and the external display.

Having worked with these simulations, however, our fantasy student remains confused. He has always thought of electricity as coming in two varieties (+ and -). The + variety comes from the positive terminal of the battery and the - from the negative pole. He now understands the new representations he has seen (electrons flowing in closed paths), but he is rightfully uneasy because his own old familiar intuitions now don't fit into this picture at all.

This phenomenon of "novice" models are identified and documented among many university-level students by many researchers (Lochhead, 1978; Champagne, Klopfer & Anderson, 1980; Trowbridge & McDermott, 1980; Trowbridge & McDermott, 1981). Gentner (1980, 1982) validated in the laboratory how certain novice models lead to characteristic errors in thinking about electricity. McCloskey and his colleagues related characteristic errors of thinking in mechanics to a set of underlying reasoning principles. Subsequent research (Unknown, 1992) developed a full taxonomy of novice models in many sciences, and began to elucidate a theory to account for them. The early work on the origin of subtraction-algorithm "bugs" (Brown & Burton, 1978; Brown & Van Lehn, 1980) contributed fundamentally to this effort.

Because of this research, our fantasy student can see on his screen simulations of how circuits work according to various common novice models. He soon finds his own, working pretty much as he had always thought. He's glad to find his views are sufficiently normal and common to appear in the computer. He finds some discussion and demonstration of evidence of his model's shortcomings. There are also a few tips describing errors that are common among people holding this model, and that he might therefore watch out for, and a few associated practice problems. However, this part of the computer instructional system is far from satisfactory. As predicted by Champagne and her colleagues (Champagne, Klopfer & Anderson, 1980), helping students to revise their models is a difficult task, and further research is still needed.

The discussion so far has presumed an exceptional fantasy student. He used appropriate simulations (rather than just equations -- common among novices). He is aware of his "novice model" and has the enterprise to explore it. Although students like this do exist, clearly we can't assume this level of learning expertise for all students (even future fantasy students). Therefore, the fantasy computer system includes a learning "coach" or "tutor". This coach is a direct descendant of earlier work specifying the rules used in good tutoring. Collins (1976) developed a set of rules used to generate the questions in an effective socratic tutoring session. Brown and others developed a coach for the arithmetic game called "How the West was Won." This coach does not advise a player on every move, which would certainly destroy any pleasure in the game. Instead the coach uses strategies for deciding when and how much advice will be effective. Brown (1983) specifies directly guidelines for designing a computer-based coach.

Brown and DeLoache (1978) contributed to computer-based coaches with their work on the mechanisms of effective study procedures (e.g., what kind of note taking is effective and why). Classroom studies starting with Gentner & Gentner (1982) began to show how to use these principles in classroom contexts (Unknown, 1992).

The early computer-coaching efforts were advanced considerably when they began to make use (Unknown, 1992) of basic research on learning, in particular that of Anderson (1982). Anderson's learning theory is rich and comprehensive, applying to a variety of tasks including learning concepts and languages, and most recently learning geometry and computer programming. Modern computer-based coaches (Unknown, 1992) include an Anderson-like learning model that is constantly updated to match the performance of the student. Thus the computer coach has a rich picture of what the student does and does not know, and uses this picture to decide what kind of advice to offer.

Today's computer coaches (Unknown, 1992) make use of two additional strands of research. First, there are several computer-based "expert-advice systems" (Shortliffe, 1976; McDermott, 1982a; McDermott, 1982b; Duda, Hart, Barrett, Gashing, Konolige, Reboh, & Slocum, 1978). MYCIN, for example, provides consultation on the diagnosis and treatment of bacterial diseases (Shortliffe, 1976). These expert systems are based on a large collection of rules, each reflecting a bit of expert knowledge. These rules are used both to generate advice and to provide an explanation of why that advice was offered. My fantasy students' computer coach uses an expert system like this, composed of rules based on research (Unknown, 1992) on the knowledge of experts in electricity and electronics. Thus the computer system can both give him expert advice on how to solve a problem and explain how that advice was determined.

Finally, my fantasy computer coach uses the work of (Reif & Heller, 1982; Heller & Reif, 1983) formulating problem-solving strategies that help students to work effectively, independent of how current experts perform the task. Their theoretical analyses were tested (Heller & Reif, 1983) by showing that students guided to use these strategies performed substantially more effectively than students without such guidance. Thus the fantasy coach incorporates the kind of guidance Reif and Heller gave to their students.

In summary, in the fantasy we have pursued, the student does his problem solving using a powerful "editor" that both structures problems for him and helps him to learn structuring strategies. Much of his work involves running circuit simulations that are carefully designed to connect relevant physics principles to meaningful representations, and to help him use these representations in solving problems. All of his activity is monitored by a computer "coach" that continually updates a model of the students' knowledge, and offers advice when needed. The coach's advice is based on research on human experts, on expert computer systems, and on independent strategies for effective problem solving for students.

3. A Research Agenda

Throughout the preceding fantasy I have mentioned research, both current research and research that is still needed to make this fantasy a reality. In this section, I summarize this research, outlining the research we needed to extend in order to make creative use of powerful computers in the classroom. I divide this agenda into the following themes: (1) Human memory and reasoning; (2) Cognitive structure of science; (3) A rich theory of learning; (4) Computers as objects of science.

3.1 Human Memory and Reasoning

To build programs that provide intelligent instruction, we need to know about the minds we are teaching. In this sense, all of cognitive psychology should be on our research agenda. However, the most needed research concerns how memory works and how people reason. For example, a study mentioned earlier (Reder, 1982) shows that after time delays of 2 days, subjects' recall of a text is accounted for better by a model that says subjects reconstruct knowledge by considering what is plausible, and less well by a model that says subjects simply recall stored facts. Thus when we want students to remember something, we must be profoundly concerned with making it plausible to them.

At this time we know little about how to make information plausible or meaningful. Further basic memory research (like Reder's) will help. In addition, we need research on the kinds of meaningful representations experts use (cf., Chi, Feltovich, & Glaser, 1981; Larkin, 1983; de Kleer, 1979) and on how these representations can be conveyed to students (Resnick, 1981; Larkin, 1983; Brown, 1983).

Largely separate from studies of memory are studies about how people reason. There is a growing literature on "novice models" -- the reasoning untrained people do about scientific topics. For example, (Green, McCloskey, & Caramazza, 1980; McCloskey & Kohl, 1982) demonstrate that most untrained individuals have fairly well-defined "principles" that they use to predict the motion of objects, and that are totally different from the established Newtonian theory. Others (Champagne, Klopfer & Anderson, 1980; Clement, 1982; Lochhead, 1978; Trowbridge & McDermott, 1980, 1981) have less formally established similar patterns of reasoning among college physics students. Understanding novice models is important in all science for the following reasons.

First, students come to us using these novice reasoning patterns. If we fail to make contact with them in our teaching, students either don't understand us at all, or they experience science as a collection of rules totally separate from their own beliefs. I suspect that novice solvers' tendency to use equations almost exclusively may come from their experience that equations never make sense (in terms of their novice scientific models) and therefore must be applied without any reference to a meaningful model of what is going on.

Second, novice scientific models are very resistent to change (Champagne, Klopfer & Anderson, 1980; Lochhead, 1978). They are seen in students with one or more years of university-physics background and in students who have experienced programs carefully designed to help them remodel their novice conceptions. Thus novice science is not a problem of introductory science, but a serious problem for all science teaching.

Finally, there may be ways to use these powerfully entrenched novice models to help students acquire more broadly correct scientific models. For example, Carbonell and I, with support from the ONR and ARI, are working to develop computer-based scientific reasoning systems that will use reasoning patterns that are naturally congenial to human beings, patterns that appear in these novice scientific models. One benefit we anticipate for this system is an ability to explain scientific phenomena in terms that are readily understood.

Powerful computers can support instructional systems that make use of extensive knowledge about how the human mind works -- how it reasons, how it stores things in memory. To make use of this capability we need continuing research on how the mind works.

3.2. Cognitive Structure of Science

To use intelligent computers in teaching science, we need to know how science is organized in the mind. In the past science educators have neglected this area of research. Experts have believed that their own intuition about how a discipline was structured was a sufficient basis for designing instruction. However, a large body of research, forcefully summarized by Nisbitt & Wilson (1977), indicates that people's intuition about their own knowledge and cognitive processes is often highly misleading.

People may believe, for example, that they solve physics problems according to a certain strategy, whereas, when they are observed, the process is found to be totally different. Thus as we think about designing more powerful methods of instruction; it is important that we base this instruction on good research into the way scientists actually think about science, rather than continuing to rely on our unreliable intuitions about these processes. The following three strands of research are relevant to this aim.

There is a growing, but still very incomplete, body of literature on how experts do science. Most of this work involves listening to the experts speak aloud as they perform various scientific tasks, and then developing computer-implemented models that account for the reasoning steps stated by the expert. For example, McDermott & Larkin (1978) developed a computer implemented model that simulated the behavior of a single expert solver on a group of five mechanics problems. In order to account for the expert's behavior, we had to postulate and develop in our computer-implemented model the following set of four separate representations for each problem: the original English language statement; a basic representation comprising the real objects in the problem (e.g., wheels and levers); a scientific representation comprising the important physics objects in the problem (e.g., forces, energies); a mathematical representation composed of equations based on the scientific representation. Subsequent work (Larkin, 1983; Chi, Feltovich, & Glaser, 1981) suggests that perhaps the single major advantage that expert solvers have over novice solvers is the ability to construct "scientific" representations of problems. These representations involve special scientific objects (e.g., energies, momenta) that are understood only by people with special scientific training. These representations have special powerful properties for use in solving problems. The workings of such representations are somewhat elaborated by more recent work (Larkin, 1983, 1982), but are not fully understood.

A second type of research that helps to clarify the cognitive structure of science is the building of computer-implemented expert systems. As mentioned earlier these systems can, at least in limited domains, exhibit an expert level of performance. Examples of such systems include the MYCIN medical diagnosis system (Shortliffe, 1976), and the PROSPECTOR system for locating mineral deposits (Duda, Hart, Barrett, Gashnig, Konolige, Reboh, & Slocum, 1978). Often examining the knowledge structure of these systems provides some insight into how knowledge in the discipline could be organized. Of course, knowledge organization in a computer system is not direct evidence that the same knowledge is organized that way for human experts. However, any knowledge organization capable of producing expert performance is probably worthy of our consideration as a structure on which to base instruction. For example, the ISAAC system developed by Novak (1977) is a moderately expert system that solves problems about systems subjected to forces and torques. This system works with a set of "canonical frames". Every system is translated into a set of these frames. Thus, for example, the system knows that in this context a person is either a pivot or a weight. When the problem has been represented in terms of these standard canonical frames, then the physics knowledge of ISAAC develops equations. These processes parallel the processes observed in a human expert by McDermott & Larkin (1978). ISAAC starts with real objects (e.g., people) and translates them into physics objects (e.g., pivots) from which it develops equations. Thus systems like ISAAC provide a very concrete formulation of the kind of knowledge we believe physics students must acquire in order to solve physics problems.

A third and currently very small strand of research also holds promise for better understanding of the cognitive structure of science. Reif and Heller (1982, 1983) have taken the novel view that effective strategies for solving problems may be quite different from those currently used by human experts and also quite different from those that are most effective for computer solvers. Indeed, the latter seems probable since humans and computers have quite different basic abilities. Thus Reif and Heller began their work with an unconstrained search for methods of solving problems that would prove effective for human solvers. They subsequently validated these formulations by showing that if students were guided (by the reading of a prepared script) to solve problems in accordance with the model, problem solving performance improved markedly. In this research we have a source of knowledge about how a scientific discipline, in this case physics, can be effectively organized for use by students.

Powerful computer-based instructional systems can potentially provide more extensive and detailed instruction than is available to most students today. However, this extensive instruction is not likely to be effective unless the knowledge it conveys is organized in a way that human beings can use effectively. As we extend the power of our instruction, we need to know in greater detail what this structure is.

3.3 A Rich Theory of Learning

The preceding themes in this research agenda have concerned first the reasoning and memory capabilities of students without special training, and second the cognitive structure of science for effective use by a skilled person. This third theme addresses the use of basic capabilities for acquiring the cognitive structure of a discipline. How does a person with normal or even superior memory and reasoning capabilities acquire an effective cognitive structure of science?

Our theories of learning in the past have been very inadequate for this issue. Psychological theories of learning have included powerful and explicit models, but only for very simple learning tasks (e.g., paired associate learning, simple concept attainment). Educators' theories of learning, in contrast, have dealt with the full complexity of human learning (cf., Ausubel, Novak, & Hanesian, 1978), but at the cost of explicitness. As we move toward the use of powerful computation in instruction, we will need broad models of learning that are explicit enough to specify how instruction should be designed.

Fortunately, the last ten years have produced explicit learning models that are rich enough to be of use in designing instruction. The best example is Anderson's ACT model (Anderson, 1976). As mentioned earlier, this model accounts for a wide variety of learning behavior. Anderson has recently extended it to account for learning in the semantically rich fields of geometry and computer programming (Anderson, 1982; Anderson, Farrell, & Sauers, 1983). The ACT learning model is based on a small number of general learning abilities that Anderson assumes are available to all human learners. For example, suppose an inference rule in the model initially applies successfully to one situation, but then produces an inappropriate result in a different situation. ACT then learns using the mechanism called discrimination. It adds to the rule's conditions for applicability a condition that discriminates between the two situations. Models of this kind may ultimately be sufficiently sophisticated that they could track the learning of a human student, and so provide the basis for the computer-implemented "coach" discussed earlier.

3.4 The Computer as Scientific Object

The preceding sections have discussed how to use powerful new 16-bit micro-computers for teaching the familiar scientific disciplines, mathematics, physics, chemistry, etc. We must not forget, however, that computers are in their own right important scientific objects. Indeed knowing something about computers is probably not as important a general educational goal as knowing something about physics or chemistry. Since computer science is a totally new discipline, we know even less about teaching it effectively than we do about teaching the more established disciplines. Thus we must include on our research agenda some considerable support for research on the effective teaching of computer science.

For example, we need to think out what aspects of computer science should be taught to what audiences. For most audiences, programming is probably <u>not</u> appropriate. But every person is likely at some time to need to interact with computers, and therefore should know at least what computers are and are not capable of doing.

In addition, most people probably should have some exposure to computer tools, for example, the editors described earlier. Other examples include tools that analyze truss structures in the design of bridges, tools that present 3-dimensional graphic pictures of objects being designed (e.g., buildings or cars), and data base programs that retrieve and sort information from huge files of data (e.g., the U.S. census data base). Certainly at the university level, in any field that is information rich (e.g., history, psychology, sociology) or computation rich (e.g., all engineering) a responsible educational program must introduce students to tools that are essential for his discipline.

Finally, computer science, in a sophisticated sense, is itself a growing discipline. Just as some of us will continue to be concerned about the education of those few people we hope will become creative physicists, some new few of us should become concerned about the education of creative computer scientists.

Table 1: Agenda of research needed to realize the potential of modern computation in science education.

Human memory and reasoning	
	What are the mental capabilities of our students? What are the general properties of mental functioning? What reasoning patterns relevant to the teaching of science are exhibited by beginners with no scientific training?
Cognitive structure of science	
	How are the scientific disciplines organized in the mind? How do people effectively store scientific knowledge and access it for use? What strategies do they use in bringing knowledge to bear on problems?
A rich theory of learning	
	Through what mechanisms do people learn? How can these mechanisms be facilitated?
Computers as objects of science	
	What should we teach people about this important topic and how shall we teach them?

4. Summary

Table 1 summarizes my research agenda. In short, we need to think broadly. Science instruction of the future can be qualitatively different because we have a qualitatively different tool. But to realize this potential, we need to generate fundamental knowledge about the human mind, about the cognitive structure of science, and about how people learn.

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THE ACQUISITION OF MATHEMATICAL KNOWLEDGE

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It might seem that mathematics is the most sharply defined subject in the world, with the learning of mathematics running it a reasonably close second. It might seem that way... as long as we do not look carefully...

I. The Emergence of the Alternative Paradigm.

In the 1950's and 1960's, when a significant number of people of first-rate intellectual power sought to improve the learning of science and mathematics, one obstacle impeding progress was a widely-held conceptualization of learning, and of knowledge, that did not do justice to reality. Put very briefly, within this view "knowledge" was measured by the selecting of correct responses to a relatively small collection of questions. What was NOT considered was the analysis that led the student to make his choice, the <u>thought processes</u> or <u>conceptualizations</u> that led to the selection of any specific answer.

The appeal of such an approach turned out to be surprisingly great, partly because of its great economic advantage, but also (perhaps even more so) because it offered intellectual simplicity. Critics of this approach were not lacking -- indeed, the remarkable career of Jean Piaget grew out of his conviction that IQ testing made a fundamental error when it focused on "right" vs. "wrong" answers, and ignored the <u>reasons</u> why people selected different answers. More recently, Krutetskii (among many others) has written sharply critical reviews of research based on answers and ignoring the processes that produced these answers. (Cf., e.g., Krutetskii, 1976.)

Piaget's precedent, and Krutetskii's criticism, went without response in the United States for surprisingly long, but in recent years an alternative approach to the study of mathematical performance has emerged, which has come to be called the "alternative paradigm." (Cf. Thompson, 1982.) It studies <u>process</u> as well as <u>product</u>, and relates observations to a postulated conceptualization of human information processing. Data is often obtained from task-based interviews; a student or expert is asked to solve a problem while one or more observers watch, and perhaps ask occasional questions (such as: "Would you <u>always</u> multiply there, or would you sometimes do something else?", which can often detect conditional processes, such as "multiply A by B if $C < D$"; or questions such as "How did you decide what to do first?", etc.). The postulated conceptualizations owe much to artificial intelligence (or "complex information processing," to use the Pittsburgh name) and cognitive science.

II. What Is Mathematics?

Unsurprisingly, a new view of how to study mathematical performance has paralleled the emergence of a new view of the nature of mathematics itself, and also of new ways that mathematical knowledge is used in today's society. When most users of mathematics performed repetitive tasks in a routine way, it made sense to think of mathematics as a specific, well-defined collection of explicit techniques, and to test skill in the performance of these specific techniques. Nowadays, routine repetitive uses of mathematics are becoming less prominent -- they can usually be automated advantageously -- and less-routine performances are becoming more common. Mathematicians and physicists have always been concerned with non-routine mathematics. Nowadays, even office workers often are. The moment one employs machines -- either calculators or computers -- much of the routine work is removed from humans, but non-routine demands increase: every new calculator or computer is likely to introduce some element of novelty and the ability to deal effectively with novelty becomes more important than the ability to deal effectively with repetition. Humans need to do what the machines do NOT do.

It is easy for those of us who are close to mathematics and science to underestimate what a profound change this implies for those who are not so close. For most office workers, tradespeople, parents, and precollege teachers, mathematics is DEFINED as a specific collection of explicit algorithms. They can think of mathematics in no other way.

Even when curriculum modernization causes a high school teacher to enlarge the specific collection of techniques, the teacher will not actually change his/her epistemologic view: math will still be perceived as a fixed collection of explicit algorithms. The adequacy or correctness of this fundamental view is one of the basic questions in mathematics education today. We shall see it reflected in several ways in what follows.

How else CAN one view mathematics? Those who are closer to mathematics typically see it as:

(1) An open-ended collection of techniques. (You are free to devise new and better techniques whenever you can, and this is seen as a REAL possibility.)

(2) A complex bit of information processing that includes:

i) Creating representations for problems, and representations for mathematical situations, knowledge, etc.

ii) Difficult tasks in selection and retrieval from memory.

[e.g., Does the series

$$\sum_{n=1}^{\infty} n \sin \frac{1}{n}$$

converge or diverge? How about

$$\sum_{k=1}^{\infty} k \ln \left(1 + \frac{1}{k^2}\right)?]$$

iii) Heuristics
iv) Setting goals and sub-goals
v) The use of meanings in constructing or reviewing algorithms
vi) The use of non-algorithmic knowledge, such as principles, etc.

Details: The preceding generalities about the nature of mathematics can be illustrated by some specific examples. Repres ations: Stephen Young has demonstrated how a mathematics problem may be easy if one representation is used, or very difficult if some other representation is used. It is well known that

$$I = \int_0^{\infty} e^{-x^2} dx$$

is a difficult problem in this form, but if I^2 is represented in polar coordinates, one easily finds that

$$I = \frac{1}{2}\sqrt{\pi}$$

As Young shows, this phenomenon goes much deeper. Young uses this fact to develop a detailed explanation of why, on each of two recent PSAT tests, problems coded with wrong answers sneaked past the experts, only to be solved correctly (and confidently) by some neophytes [Young, 1982].

Indeed, Young goes even further, showing how the alternative representations can be built up from simple ingredients learned in everyday experience [idem]. An Open-Ended Collection of Algorithms. One instance of a student inventing a new algorithm was reported in [Barson, Cochran, and Davis, 1970]; many others have been reported. Cf. Suzuki [1979], Kumar [1979], or the series of studies on addition carried out by Resnick and her colleagues [1978]. Any experienced mathematics teacher sympathetic to student originality will have seen many more. Heuristics: The importance of heuristics is generally well-known [cf., e.g., Polya 1965; Davis, Jockusch, and McKnight, 1978].

The willingness to use non-algorithmic knowledge has emerged as one of the differences between expert and novice performance. Cf., for example, the following problem from a calculus book:

> A rope with a ring in one end is looped over two pegs in a horizontal line. The free end, after being passed through the ring, has a weight suspended from it, so that the rope hangs taut. If the rope slips freely over the pegs and through the ring, the weight will descend as far as possible. Assume that the length of the rope is at least four times as great as the distance between the pegs, and that the configuration of the rope is symmetric with respect to the line of the vertical part of the rope. (The symmetry assumption can be justified on the grounds that the rope weight will take a rest position that minimizes the potential energy of the system.) Find the angle formed at the bottom of the loop.

In task-based interviews, Davis [1983] found that two students in a class of 22 saw this as a problem involving a <u>principle</u> -- that the weight will descend as far as possible, or that its height will be a minimum -- and were thus able to solve it, whereas other students tried (in vain) to recall a formula that would give the solution. (No explicit general <u>formula</u> exists, but the applicable <u>principle</u> is stated twice within the statement of the problem.) Beginning students are strongly disposed to view mathematics as a specific collection of formulas and algorithms, a phenomenon which needs to be understood better. It is true that these students have typically had teachers who viewed mathematics that way, but this fact does not establish cause and effect. Do students acquire this view from their teacher (which would be no mystery)? Or is the algorithmic view so natural for beginners that the students have compelled their teachers to see (and teach) mathematics this way? (It is certain that many students are not easily induced to abandon the algorithmic approach. Cf., e.g., Davis, <u>Learning Fractions</u> [in preparation].) A persistent difference between novices and experts is the tendency of novices to see their work as a sequence of small steps, often neglecting well-known <u>meaning</u> [cf., e.g., Davis and McKnight, 1979], whereas experts see larger "chunks," more often in the form of principles or of typical situations (or problem types). Clearly some of this difference is inevitable, but the observed differences often seem extreme, and may be the result of learning experiences that neglect larger patterns in favor of a sequence of smaller steps. [Cf., e.g., Beberman 1958; see also Larkin, McDermott, Simon and Simon 1980].

III. Learning Mathematics

A. Given the situation described above, it may be no exaggeration to say that a fundamental question of mathematics education is the following:

> Which should come first,
>
> <u>understanding</u> <u>or</u> <u>algorithms</u>?

Nearly every school program in the U.S. that has been carefully observed has focussed mainly on <u>algorithms</u>. To non-mathematicians, mathematics <u>is</u> algorithms. [Eg., "to divide fractions, invert and multiply."] Reports are especially numerous on addition and subtraction involving "borrowing" and "carrying." These topics are nearly always taught, and learned, primarily as rote.

It does not have to be this way. Dienes' MAB blocks provide an excellent opportunity for students to get experience with place-value numerals. In the base ten version, the smallest block is called a unit, and is a cube approximately 1 cm. on an edge. Next larger is a "long", which can be thought of as 10 units lined up and glued together (although of course it is not manufactured that way). Next comes a "flat", ten longs placed side by side and glued together. The largest block can be thought of as ten flats, stacked up, and glued. Any decimal numeral not larger than 9,999 can thus be represented by an array of base-ten MAB blocks. There is a unique canonical representation if one observes the rule that "thou shall not have 10 blocks of the same"; these representations are isomorphic to standard decimal numerals. But just as the canonical representation "64" in

$$\begin{array}{r} 64 \\ -\ \underline{28} \end{array}$$

allows alternative representations

$$\begin{array}{r} \overset{5}{\cancel{6}}\,{}^{1}4 \\ -\ \underline{2\ 8} \end{array}$$

so, too, do arrays of blocks (if one allows violations of the "thou shall not..." rule) -- in this case, 5 longs and 14 units.

Many alternatives exist for the use of MAB blocks, and presumably some of these are more effective than others. But the underlying fundamental issue is: what different forms of learning result if a student first works with MAB blocks and "trading," or if he/she first works with numerals and procedures for operating with numerals? (It <u>is</u> known that many school programs using MAB blocks are ineffective, in that thinking in terms of blocks is not allowed -- by the children -- to intrude into their thinking about writing numerals on paper [Davis and McKnight, 1979]. This, of course, is no argument that <u>other</u> ways of using MAB blocks might not succeed.) [Lauren Resnick also has some data on this question. There are so many different ways of using MAB blocks that the question is not easily settled. Present evidence seems to support the unsurprising result that the effectiveness of using MAB blocks depends upon how you use them.]

B. Constructivism.

Two themes have emerged so strongly in mathematics education research that they have come to be regarded as a definite research posture, which has been given the name <u>constructivism</u>. The first theme is the assumption that <u>a new idea is built up by modifying or combining ideas that the learner already has</u>. When stated that directly, the assumption sounds so familiar as not to deserve comment. But, when taken as a serious indication of how one can go about studying the knowledge in a student's mind, the proposition has important implications, and is supported by a growing body of evidence.

Before considering it in detail, it is helpful to state also the second theme: the foundation on which this pyramid structure of "new ideas" is built can often be traced back to ideas that were learned early in life.

What does this mean? Or, perhaps equivalently, how does one study such matters?

In quite a few different ways. One can study language, for example as used in U.S. newspapers. One easily finds instances where abstract or intangible matters are described as if they were tangible matters, of the type that a young child meets in the first five or six years of life: "Because he had previous convictions for perjury, the jury gave little weight to his testimony." "The burdens of the office seems to weigh heavily on the President's shoulders." "He stuck fast to his contentions and refused to be shifted." "Sticking", "shifting", "refusing", "weight", "heaviness", and so on, are clearly the kind of thing that a child has experienced very often in the first five or six years of life.

One can study the role of metaphors in the representation of knowledge. How would people have interpreted Rutherford scattering if they had lacked the "solar system" metaphor? Quinn (1982) has studied people's discussions of marriage (most commonly represented as a journey, or as a container, room, or enclosed space ("...affairs outside of the marriage..."), or as a valuable product ("...to build a good marriage..."), or as a contract or agreement or job ("...not doing his/her share..."), or as one of a few other common metaphors), and Dedre Gentner has carried out a long sequence of fascinating studies on metaphors used to think about quantities or situations in physics and engineering. (Gentner, 1980A, 1980B; Gentner, 1982).

One can study unconscious gestures. David McNeill, of the University of Chicago, has videotaped mathematicians talking to one another. In one interview, Mathematician A is explaining something to Mathematician B (who obviously has a strong general knowledge of the area in question). The earlier part of this interview establishes that A has some unconscious gestures. Whenever he says "inverse limit" he rotates his right wrist as if he were screwing in a screw. Whenever he says "direct limit" he extends his right hand outward, somewhat like a salute (or perhaps someone lauching a pigeon into flight). What makes this interview especially interesting is that, in the second half of the interview, Mathematician A makes several slips of the tongue, saying "inverse limit" when he means "direct limit," or conversely. In each case, B corrects him, and A acknowledges the correction.

However, in every case where the wrong phrase was uttered, the correct unconscious gesture was employed (so that, in these cases, the phrase pronounced did not match the gesture used).

Clearly, A's internal information processing is using some representational system different from his words, and only in a last stage was the representational knowledge converted into natural language statements as an "output" product.

More direct evidence for this same conclusion has been reported by Marshall (1982), Marshall and Newcombe (1966), and Newcombe and Marshall (1980), in cases of patients with brain lesions that blocked the communication within the brain. For some of these patients, internal processing was unimpaired, but communications between some language functions were blocked, making it possible to get a more direct view of how the internal processing itself was carried out. [For example, in one form of disorder, patients read the printed symbol

glad

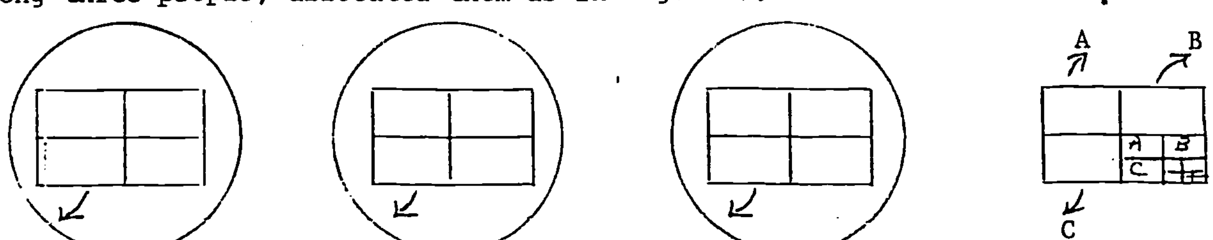
as "happy", believing that they had read it correctly. Clearly, no reasonable theory of phonics or direct visual-acoustic associations could explain this. The printed symbol "glad" must have been translated into some internal mental symbol, which was in turn translated into the oral response "happy".]

The fundamental role of representations drawn from early experience -- even when one is dealing with extremely abstract and complex matters -- is not really mysterious. If you wanted to explain "one-to-one correspondence" to someone who was not a mathematician, how would you do it? How would you explain continuity of a function $y = f(x)$? How would you explain the addition of e.m.f.'s when batteries are connected in series?

On the other hand, the constructivist view of mathematics is something new - at least to most people. For one thing, the prominence of metaphors has, in the past, often been regarded a a convenience employed in interpersonal communication. The constructivist sees it as something far more basic -- these "primitive" metaphors are essential parts of one's internal representations of abstract ideas -- they aren't just "communication," they are how you yourself think about these things. [Cf., e.g., Lakoff, 1982.] When you think, you think metaphorically!

Why is this important? Partly because schools do NOT usually view mathematics this way, and do not teach it this way. Ginsburg (1977) has noted the discrepancy between the way children think about mathematics on their own, and the way they do in school (because of the school's expectations). Underlying this discrepancy is the gap between the school's view of mathematics as verbal and algorithmic knowledge, and the reality of mental representations building upon earlier non-verbal representations within a child's mind (or an adult's, for that matter).

Kieren, Nelson, and Smith [to appear] report the performances of some seventh and eighth graders on fractions concepts in non-notational settings, where they are able to use their "primitive" representations. One eighth-grade girl, asked to divide four rectangles ("candy bars") equally among three people, allocated them as in Figure 1.



Give this candy bar to Person A | Give this candy bar to Person B | Give this candy bar to Person C

Figure 1

That is to say, she gave each person one whole "candy bar". One bar was thus left over. She respected the indicated division into fourths: she gave one quarter to each person. One quarter was now left over.

She continued this process, always dividing the "left-over" portion into fourths, giving one to each person, and having one left over.

In effect, she determined that

$$4 \div 3 = 1.1111\ldots \text{(base 4 numeral)}.$$

This student could not have dealt with this within conventional abstract notations, but in a setting where all of her "real world" knowledge (about dividing into halves, or halves of halves, etc.) could be brought into play, she was well able to solve the problem, showing an unexpected level of ingenuity. (Admittedly, if she had divided a remaining piece into thirds she could have made the process terminate.)

Lave et al. (in press) report the contrast between the unsuccessful efforts of some adults to solve some mathematics problems in paper-and-pencil settings, vs. their success with similar problems in concrete settings in supermarkets, in their own kitchens, etc. [One man's diet called for him to eat three-fourths of the cottage cheese in a cup that was two-thirds full. He spread out some wax paper, arranged the cottage cheese on it as a disc, marked two perpendicular radii -- thus getting fourths -- and took three of them.]

This pattern shows itself time and time again -- students (or adults) who are creative, resourceful problem solvers in familiar situations, but who are unable to carry this resourcefulness into "abstract" mathematical situations, even though the problem structure may be essentially the same in both cases.

We would argue that the task of an effective educational program is to establish problems and resourceful problem-solving at some appropriate level, which (for some students) may be as concrete as these examples, and then to carry these problems and this resourcefulness along a developmental path into -- ultimately -- conventional notations.

Schools -- and, all too often, nowadays, university freshman courses -- usually fail to do this.

To be sure, a mathematician can deal with the definition of, say, the limit of a sequence in the form:

The number L is the limit of the sequence

$$a_1, a_2, a_3, \ldots, a_n, \ldots$$

if, given any $\varepsilon > 0$, there exists an integer N such that

$$n > N \Rightarrow | a_n - L | < \varepsilon .$$

However, this same mathematician will often think of this concept in terms of something closer to Figure 2.

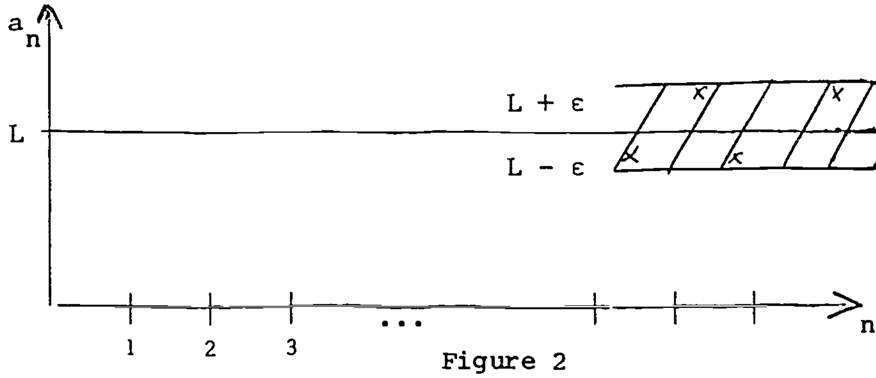


Figure 2

In Figure 2 we again see the prominent role of such simple, early ideas as "nearness" and "there is" ("there exists") and "if you go far enough". The combined effect is sophisticated and powerful -- but the constituent building blocks are very simple ideas, which must be carefully assembled and carefully juxtaposed.

But of course the main point is that the successful mathematician has, with great effort, built up a conceptual structure from "primitive" ideas about magnitude, measurement, nearness, distance, through an elaborate structure of coordinates, truth values, implication, indirect proofs, etc., until he or she can deal effectively with statements about the "existence" of some unspecified integer of wholly-undetermined magnitude. (How large is that N, anyhow?)

Today's educational programs typically fail to promote this development in most students. (Freshman college calculus and physics courses -- as actually taught -- are not entirely exempt from this criticism!)

This situation helps to explain both some of the success, and some of the failures of the "new math" programs of the 1950's and 1960's. The best of these programs did begin with such concrete experiential knowledge that virtually every child could deal with them -- and children did learn this material well when it was taught by, say, a David Page, who used this strategy consistently. This conception of knowledge and this approach to teaching were, however, so foreign to the conventional wisdom of schools that the method could not be used in most schools, nor by most teachers.[1]

The reader can observe directly how very simple ideas such as distance, symmetry, interchanging A with B (well-known to young children in their

[1] The Page approach -- or something recognizably akin to it -- has been advocated by Polya (1965) and used by Bertrand Russell (1958), among others. It has been discussed elegantly by Papert (1980), Minsky (1980), Lawler (1982), and others.

spontaneous play), and so on, are employed in thinking about abstract matters. Consider the fraction y = f(x) defined by

$$y = \frac{1 - x}{1 + x}$$

This has the weird property of being its own inverse:

$$y = \frac{1 - x}{1 + x} \qquad\qquad x = \frac{1 - y}{1 + y}$$

What are the necessary and sufficient conditions for this to occur, expressed geometrically? Expressed algebraically?

What basic ideas did you use in thinking about this problem? Even though they may have been expressed by sophisticated representations, if you trace them back to the previous "foundation" ideas they were built on, and trace those ideas back to what they were built on... and so on... you find a foundation in the experiences of a child who may be 3 or 4 years old.

Interchanging x and y to turn f (x,y) = 0 into f (y,x) = 0 is recognizably based on such simple ideas as interchanging two blocks of the sort that children play with. The remainder of this discussion is left as an exercise for the reader.

An elegant description of this phenomenon of building complex ideas on a foundation of simpler ideas is given in Papert's Mindstorms (1980), where he describes how, when young, he was given a set of gears which he studied deeply for a long time. The ideas gained from concrete experiences with the gears later provided a foundation for sophisticated ideas about equations, causality, ratios, and so on.

Lawler (1982) has studied both cause and effect in his careful observations of his own children. In particular, in working with a computer (using the LOGO language), his young son Robbie learned the value of studying a new situation by systematically stepping one controllable variable. Subsequently, in a wholly new setting (cutting paper loops to study the resulting configurations), Robbie made effective use of this same method of stepping (incrementing) one variable at a time.

SUMMARY. In my view there is compelling evidence that the key ideas of mathematics are NOT expressed in natural language while they are being processed within the human mind. These ideas are often converted to natural language for output purposes, just as some computers in Saudi Arabia present outputs in Arabic, although a program entered into the machine in Arabic will be converted by the machine to English (and BASIC, APL, etc.), thence to machine language, processed, output in English, and (in some cases) converted into Arabic listings for the convenience of Arabic-speaking programmers.

This is important for a variety of reasons, including these:

1) Today's school programs are overwhelmingly verbal, natural-language affairs. The basic, experiential concepts may fail to be developed in many students.

2) CAI may make matters worse, since it so readily lends itself to precisely this abuse. ("That CAI which is most easily written, should NOT be." A new Murphy-type law proposed by Jerry Johnson (1982).)

3) Someday someone needs to take a new look at courses in physics, chemistry, calculus, etc., as typically taught in high schools, community colleges, and freshman university courses. The "mathematical" content -- formulas, mainly -- appears to be very great, including formulas from special relativity and from quantum mechanics -- but this content is presented unrelated to the ideas of physics and chemistry. The sophisticated content of PSSC has been seized upon as a precedent to be emulated, but the ripple tanks and racing cars and rotating platforms have been left out.

> [We observed some students trying to solve this problem (from p. 815 of Halliday and Resnick):
>
> 15. (a) What is the separation in energy between the lowest two energy levels for a container 20 cm. on a side containing argon atoms? (b) How does this compare with the thermal energy of the argon atoms at 300K? (c) At what temperature does the thermal energy equal the spacing between these two energy levels?
>
> The students treated this as a hunt for the correct formula, and showed little knowledge of, or interest in, the actual physics of the situation.]

A main message of PSSC, David Page's project, and so on, has been lost: the need for the gradual experiential development of CONCEPTUAL and INFORMATION-PROCESSING foundations, often by NON-VERBAL means.

It seems that one of the great strengths of humans has contributed to one of the great weaknesses of educational programs: humans can often sound as if they know what they are talking about, when in fact they do not.

C. Principles of Instruction

On another matter, one of the great strengths of the Curriculum Improvement movement has nearly been lost: the use of a different set of principles of instruction. No compilations or analyses of this seem to have been made (with the exceptions of Howson, et al.,(1981) and Hayden (1982)), but it may be appropriate here to acknowledge their existence and to present one example:

What Do You Want Students to Learn? (The "Tool" Principle.)

A principle used by some "new math" projects was sometimes called the tool principle: every mathematical concept or technique or strategy or algorithm should be seen as a TOOL to accomplish some worthwhile goal. Typical school programs, then and now, make little or no use of this principle. The sin ϕ may be defined as "the opposite side over the hypotenuse" (or in other, more circumlocutious, ways), but this does NOT appear as an answer to a recognized need. When one follows the "tool" approach, it does. The need may be to determine the height of a flagpole in the school yard; the sin (or, more likely, the tan ϕ or the cot ϕ) can then be concocted as a tool for solving this problem. This is not artificial; it is true to the nature of mathematics. Every piece of mathematics is created as the response to a sensible challenge, and students should see it that way. Few do.

The contrast can be seen clearly in the treatment of the field axioms as a foundation for algebraic operations. One "new math" project presented this use via a sequence of activities, each sharply targeted at a specific learning goal. One activity was a game where, from two sentences, students were asked to infer a third; this activity was intended to provide an experiential basis for the idea that some collections of statements can imply others. Another activity was the use of the word puzzles found in newspaper puzzle sections: Start with, say,

S O U P

and end up with

N U T S.

At every line you must have a legitimate English word, and to get from one step to the next, you may make a change at only one place in the string of leters -- the last letter, say, might be changed from a "P" to an "R", while the first, second, and third letters remain unchanged. This activity is intended to provide an experiential foundation for the idea of changing a symbol string according to precisely specified "legal" rules. What is legal is specified with considerable precision, but the strategic choices of what would be useful (would move toward the goal) is left as a creative planning task for the student. A third task combines these first two ideas, by starting with, say,

$$A + (B \times C) = A + (B \times C)$$

and deriving

$$(C \times B) + A = A + (B \times C),$$

by explicit, careful use of the commutative laws. This treatment follows (more or less, anyhow) the tool requirement. A problem is to be dealt with, and a certain method (or concept, or technique, etc.) is used to deal with it. The thing to be learned is presented in so clear a form that it more-or-less has to be learned.

By contrast, typical treatments of this same topic, as observed in some U.S. schools in the fall of 1982, violate the tool principle. They are vague in their specification of what students should learn, and the learning activities allow for the learning of undesirable or incorrect "knowledge." A typical example asks for the solution of the equation

$$0 = 7m + 4 - 3m$$

by using (a modified set of) the field axioms. This problem confuses many goals. If the goal is to find a replacement for the variable m that will produce a true statement, one does NOT need the field axioms. Indeed, most students can guess, or use trial and error, or use analogical reasoning, or graph y=7m+4-3m. Hence, students typically learn that the axioms are an unnecessary complication of an otherwise simple task. This is NOT one of the things we want students to learn about mathematics.

Even worse, the details of this problem are so complex, and both teachers and students have so much informal knowledge (and so little familiarity with the axioms), that it becomes difficult to say whether one did, or did not, follow the rules correctly. For example, if you decided that you need to use the associative law for addition, then you must turn the "subtraction" into an addition:

$$0 = 7m + 4 + [^\circ (3m)],$$

where °(3m) denotes the additive inverse of 3m. But how does one construct the additive inverse of a product? In recent observations, both teachers and students merely replaced "3" with "-3". What axioms or theorems were used to justify this? (In this case in question, none were; the matter was ignored.) Thus, instead of learning a careful use of precise rules, the student was learning a careless accommodation to a set of ill-defined rationalizations which were, in any event, perceived as merely gratuitous obstacles of the sort that give meaning to the word "academic." Is this what axioms are?

Further, whereas ingenuity in recognizing goals, setting sub-goals, and devising strategies to achieve these sub-goals should be one of the main skills to be learned, it was virtually absent from the lessons in question. The students were merely told "automatic" algorithmic procedures for solving equations of this type.

The careful and appropriate specification of desired learning outcomes has proved to be a very troublesome matter. Frequently (as we would argue was the case in the "solution" of 0=7m+4-3m) these goals are very poorly chosen, not aimed sharply at major mathematical ideas. Testing to determine what has been learned shows this same flaw. The attempt a decade or so earlier to use explicit written specification in the form of so-called behavioral objectives was a disaster, because it focused on minute matters instead of large ones, it emphasized the explicit and ignored the elusive, it dealt with behaviors when it should have dealt with ideas (or "products" when it should have dealt with "processes"), and it fostered the illusion that a curriculum in, say, calculus could be designed and implemented by people who did not themselves understand calculus.

Somehow, this unhappy history must be seen as informing us of weaknesses in some of our common research paradigms. Care in research is supposed to protect us from error, but evidently it does not always do so. Self-consistent systems can be created and operated while the reality they are supposed to deal with leaks out through cracks in the basic conceptualization.

SUMMARY: It may be desirable to pay more attention to the various "principles," whether implicit or explicit, that play a role in shaping learning experiences, and in determining what the student actually learns.

D. Some Typical Research Results.

In this section we summarize, very briefly, eleven themes from recent research results:

1. A very large number of students can learn considerably more mathematics than they typically do at present. (Johntz (1975); Kaufman (1964); Swinton, et al. (1978); Davis, Jockusch, and McKnight (1978); Dilworth (1973); and others.

2. The discrepancy is particularly pronounced in the case of mathematically-gifted students (Julian Stanley and his colleagues (1977); Kaufman (1964); Suzuki (1979); Kumar (1979); and others).

3. At the same time, there is bad news as well as good. Many students are in fact learning far less than they are believed to be learning. For example, Clement studies students who were believed to have successfully completed 9th grade algebra, the study of quadratic equations and simultaneous linear equations and conic sections and even more, but who could not answer correctly the questions:

> In a certain college there are 6 students for every professor. Write an equation to express this fact, using P for the number of professors, and S for the number of students.

The common wrong answer, of course, was

$$6S = P.$$

The error was not a casual "slip of the pen." On the contrary, students making this error were convinced that they were actually correct, and vigorously resisted efforts to change their minds on the matter. [Rosnick and Clement, (1980) Davis (1980).] DiSessa reports on students who have "successfully" completed a year of college physics, but for whom dynamics is really still Aristotle's dynamics, not Newton's (1982). Burt Green and his colleagues report the same phenomenon [McCloskey et al., 1980]. [Note that the "bad news" in (3) does not contradict the promise of (1) and (2).]

4. Mathematics is more diversified than most parents and teachers assume. In particular, it is NOT merely a collection of memorized algorithms.

5. Students in many curricula are seriously deficient in understanding what they are doing (see, e.g., Alderman et al. (1979)).

6. Careful analysis of errors can give important information about thought processes, and can guide remediation efforts (VanLehn 1982; Matz 1980; Erlwanger 1973; Davis 1980).

7. Generally speaking, more effective mathematics instruction is based upon creating an experiential foundation and building carefullv upon already-established ideas [Papert 1980; Walter 1968; Kieran, et al., to appear; Lawler, 1982; Ginsburg, 1977; Lave (in press); and others.]

8. Computers can play a role in the preceding matters, sometimes in desirable ways, sometimes in undesirable ways. (Papert 1980; Lawler, 1982; Alderman et al. 1979; Swinton et al. 1978; and others.)

9. It is advantageous, if not essential, to provide an active role for the learner.

10. What can be taught within a school classroom is constrained by:
- (i) the teacher's knowledge
- (ii) the teacher's personal values or personal philosophy
- (iii) the use of the curriculum as a tool to maintain social control within the classroom social situation.

[We shall return to this topic in a later section.]

11. Recent ETS reports indicate that minority students are "closing the gap," at least as measured by PSAT scores.

Reports from the Center for the Study of Reading (Richard Anderson) indicate a situation in reading that seems to parallel the situation in mathematics. Too much attention paid by the school to the mechanics of "calling out words" appears to hamper the growth of real power in reading (which means, of course, primarily comprehension).

IV. Do You Need A Theory?

Not only does the "alternative paradigm" in mathematics education research use task-based interviews, error analysis, etc., to get information about student thought processes, it also tries to develop, from postulated foundations, a theoretical conceptualization of these thought processes.

Is this necessary?

Looking at the history of physics, chemistry, and biology suggests that it is. How far could chemistry have developed if it had dealt only with more-or-less directly measurable quantities, such as combining ratios, densities, pH, etc.? The periodic table, and electron layer explanations of the periodicity, etc., played an essential role without which modern chemistry could not have been created. [Cf., especially Matz (1980); Minsky and Papert (1972); Minsky (1975); VanLehn (1982); Minsky (1980); Davis (1983).]

V. Schools

Any consideration of what mathematics is, and how people can (or should) learn it, must sooner or later come face to face with certain attributes of schools (although several present-day writers believe that, in the future, more mathematics will be learned outside of school than inside).

Some recent observational studies of some schools in Illinois emphasize four points, none encouraging:

1. Schools continue to be "wordy" places. There is a great deal of talk. It seems to be assumed, implicitly, that knowledge can be transmitted to people by telling them things in natural-language formulations;

2. What can be taught is presumably limited by a teacher's own knowledge of the content. Within mathematics and science this poses severe problems;

3. What can be taught is limited by the personal values and personal philosophy of the teacher (and the expectations of the school). One teacher, preparing for a mathematics lesson, remarked to the observers: "Never set out without knowing exactly where you're going!"

How do you reconcile this with Alexander Fleming's remark: "The job of a scientist is to look at something that a thousand people have looked at, and see something that no one ever saw before"? It is no wonder that "discovery learning" and laboratory exploration encountered opposition in schools. They represent direct challenges to the personal values of many teachers.

4. Finally, as Karplus and many others have pointed out, for many schools the prime role of the curriculum is to provide a tool whereby the teacher can maintain social control in the classroom. This surely explains some of the popularity of workbooks and written exercises, and the unpopularity of discussion sessions. Students can be kept orderly while they are answering routine questions, perhaps on paper. When they are asked to work together to think through some perplexing matters of some subtleties, they are not so easily controlled. (Cf., e.g., Cusick, 1973; Cusick et al., 1976.)

It is NOT an inevitable attribute of all schools -- we have found some exceptions -- but it is the common rule in most. (Oettinger's Run, Computer, Run deals with this briefly -- e.g., "No one is an individual in the language lab!" So does Silberman's Crisis in the Classroom.)

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SCHOOL MATHEMATICS: A TEACHER'S VIEW
AN AGENDA FOR RESEARCH

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TABLE OF CONTENTS

Introduction

A teacher's view of the potential that information technology has for improving teaching and learning grows out of classroom experience. Almost all teachers understand both the possibilities for use of the new equipment and the practicalities involved. They realistically appraise the problems associated with using new systems and their ability to overcome these problems.

The opportunity that technology offers education is as real as the burden educators bear if they take that opportunity. The challenge is to develop the methods that will allow teachers to take advantage of technical progress within the limits of their time, training, and the reality of the classroom environment.

Today, new technology can be applied to improve curricula in over a dozen ways. We must overcome the problems to fully realize the educational benefits for teachers and students alike. Research is the key to those benefits.

Areas of Opportunity and Challenge

1. Teacher Training

At a time when having talented teachers of science and mathematics is essential, the nation faces a crisis. The quick solution -- attracting talented students to teaching careers -- is difficult in the face of low starting salaries, attractive offers from industry, and the disfavor with which some view university education programs.

An alternative solution lies in in-service teacher training; however, the building consensus nationwide is that the current status of in-service training is unacceptable and that major changes are needed to upgrade the system. Interestingly, new technology may be an important part of that solution; in fact, it may have a unique role to play in teacher training. This technology must be both the subject and method of in-service training. The new capabilities of computer, video, and communication systems offer a potential which must be tested in the schools and with teachers.

A Teacher's View

Already industry has been able to justify the expense associated with methods of instruction involving new technology. It would be a sad statement on the nation's priorities if the companies which sell computers and securities can justify instructional investments for their employees but education cannot justify the expense to train teachers. In view of the expense, it is not clear that the private marketplace can undertake an ambitious program to prepare materials for training teachers.

Certainly, this approach toward in-service training deserves to be the subject of testing and research. We need to know whether teachers are comfortable teaching with a method from which they themselves have never learned. If there are proposals to use computers and other technology in the teaching of children, it would be wise to have teachers who have benefitted from this teaching method. It is difficult to use a method based on theory and promise rather than personal experience. Yet, for the potential of the new technology to be realized, there must be people in local school systems who can make it succeed. If funding for the equipment is a problem, then the initial expenditures for equipment and software must go toward the critical area -- teacher training.

If the technology is not successful with adult teachers, there is little point in discussing its potential for students in the classroom. Even more to the point, if these new approaches are to be used in the classroom, teachers must be trained. What better way to do the training than with the method to be taught?

2. Content and Time on Task in the Elementary Grades

Many educators feel that a major teacher training effort is necessary to improve the teaching of science and mathematics in the early grades. They believe that training should be focused on content as well as methods in order to be effective. Without training, teachers lack confidence in teaching the subject and may question the efficacy of recommended approaches. All teachers are concerned about the inability of students to solve problems, even those problems requiring the most straightforward application of arithmetic facts. Research must be conducted to see if new approaches can help to address this problem.

Among the many other questions that need answering is a difficult one related to the required computer hardward for instructing very young students. Must the hardware be sophisticated (expensive) for teaching at this level or would large numbers of the small capacity, general purpose units be suitable? Must there be equipment in every classroom or should it be clustered in a central laboratory?

Answering these questions involves exploring the type of instructional applications for which the new technology is suitable. The answers are fundamental to evaluating potential uses of the new technology in the early grades. This is difficult as there is a tendency to apply the available equipment (one knows that it can be purchased) instead of working from the top down and designing the machine with the application in mind.

Unfortunately, the current situation may be a worst case scenario: on one hand, administrators are not convinced the applications have enough promise to justify expenditures for expensive equipment; on the other hand, they do not expect to have a pool of teachers trained to use the affordable equipment in substantive ways.

Two immediate steps are suggested: research should be undertaken to provide answers to questions posed above; teachers and administrators should be given opportunities to learn enough about alternative methods to make informed decisions for their particular school and situation.

3. The Middle Grades

When teachers meet to discuss ways to improve school mathematics, many agree that something goes amiss in the middle grades. Middle grade teachers report that their students arrive with poor preparation from the lower grades. After discussion, proposals usually are made, and attention quickly turns to the status of high school mathematics. Soon there is disagreement on what should be done at that level.

It is almost as though the excitement lay in discussing the symptoms rather than attacking the problems. One of the basic reasons for this indecision and inaction in solving middle grade mathematics failure is teachers' frustration at not knowing what needs to be done and their realization that many colleagues, who have the training to teach in the middle grades, chose to teach in the high school, where again, there is a shortage of trained teachers and a better teaching environment.

The new technology has a role to play in improving mathematics teaching in these critical middle grades. For example, there must be a way to capitalize on students' fascination with video games. There also should be a possibility of using methods now available through teleconferencing, video disks, and computers to provide specialized instruction for accelerated or remedial students.

Certainly, the remedial student should be able to benefit from new delivery systems for instruction. It is sad to see teaching methods which have already proved a failure with remedial students being used with these same students.

Perhaps the new technology offers an alternative method of teaching Algebra 1 and Algebra 2 in the middle grades, where the small numbers of students or the unavailability of trained teachers make offering the courses a difficult undertaking.

Currently, there are not many affordable alternatives to structured classes, tutoring, workbooks, and ditto sheets, but the new technology has the potential to change the situation. It is worthy of extensive research.

4. Advanced Courses at the High School

Many schools suffer from a lack of faculty prepared to teach advanced courses in mathematics, science, and foreign languages. Efforts should be made to provide an alternative method of instruction for the often small number of students prepared to take these courses. This particularly applies to rural schools where teleconferencing, video disks, and computer networks could be used to provide a student an opportunity to learn and to face challenges currently unavailable. The master teacher idea once envisioned with television may be successful with video disks, teleconferencing, and computer networks.

5. Early Identification for Remediation

For a number of reasons the testing in schools today is not always accomplishing its purpose. The style of testing may be disruptive to a school program; often the results are returned in a form that cannot be processed in a sophisticated way by the local unit; and expertise necessary for the successful use of diagnostic and prescriptive tests is not always available at the local level.

Recent advances in teleconferencing and computers may provide significant help in this area. At a minimum it would appear to be possible to use a microcomputer to grade tests, to develop software to enable local districts to process test data easily, to design inexpensive computers which can administer interesting tests (tests which are chosen from a large collection of problems so that two tests do not have many questions in common), to use teleconferencing for training staff in interpreting test results, and to offer remediation in a variety of delivery systems. Computers and video disks may be particularly good for implementing an individualized testing program for mastery based learning.

6. Handling the Wide Range of Abilities in the Classroom

Individualization is extremely difficult in today's classroom. The new technology makes a variety of approaches possible. Research must be carried out to ascertain the effectiveness of new approaches toward instruction at various levels of education. Recommendations for a successful mix of modes of instruction are essential to help local districts spend limited funds wisely.

7. Treating the Applications of Mathematics

8. Doing Justice to Computer Literacy, Computer Programming, and the Computer as a Tool

9. Covering the Material in the Syllabus

10. Including Additional Topics in the Curriculum

When one reads the syllabi for courses in the mathematics sequence, one is struck by two facts: 1) it is very much a calculus sequence for those who are in a college preparatory program; and 2) the syllabi could not possibly be an accurate description of what is actually being taught. This last point is of utmost seriousness. If the syllabi were being covered, the achievement of the students would be vastly different.

Also, if the syllabi were to be covered, the mathematical background of teachers would need to be different. Since the teachers are unable to cover fully the desired course material, suggestions to include additional topics are viewed with skepticism. Teachers realize that additional topics should be included in the curriculum, that students should receive an introduction to the computer, and that applications deserve better treatment in the curriculum; however, in the teacher's view, attempting to include these topics in courses where important parts of the subject are already being omitted is unrealistic and leads to disappointment.

The failures in execution of the current curriculum are serious; the problems occur across all grade levels. Clearly, we must address them in order to establish a classroom environment which is flexible enough to permit changes in the educational methodology and which is conducive to the full development of recommended changes.

Again, it is possible that the new technology can be a major tool in enabling teachers to give proper coverage in their courses. This would especially be true if the treatment of the topics in the early grades ensured that each student arrived at the next grade better prepared. Just as calculus in the schools is often taught on a poor algebra and precalculus base, many current applications of computers in the schools are applied over a syllabus as though the mere presence of computers will improve the quality of instruction. It is of some concern that most attempts to improve instruction are "layered products" over a possibly "deteriorating operating system" (the quotes are those of the authors).

11. Student Behavior

It is awe inspiring to contemplate that teachers must work both with wonderful young people (some brilliant, some not so gifted, some motivated, some unmotivated) and with other young people who in a few years will be winding their way through an overcrowded judicial system or shortly be dead as a result of violence. The broad spectrum of people served by the schools is both a strength and weakness. One weakness will have direct bearing upon the success or failure of introducing technology into the classroom.

Systems designed to aid instruction cannot always be placed in a classroom of well-behaved students, and educators cannot assume that expensive equipment will not be open to vandalism. This is a sad situation, but many great theories are "murdered by a gang of cruel facts" (Kafka). Research must be conducted in representative teaching environments to ascertain the approaches that have a chance of success in a "real" school as opposed to the theoretical school of our hopes and wishes. Administrators are well aware of the true situation in their schools and will not fund programs which do not address this environment.

Poor student behavior is often attributable to a feeling on the part of the student that school is irrelevant. Given current manpower shortages in fields requiring training, what could be more relevant than vocational training utilizing the new technology? It is a question worthy of research.

12. Implementation of the NCTM "Agenda for Action"

13. Modernization of the Attitudes Both of Parents and Teachers Cited in the NCTM "PRISM" Summary

A reading of the "Agenda for Action" reveals that the list of eight recommendations was a product of much thought and discussion. Teachers support the recommendations, which are sensible and yet innovative, but there is a sadness in viewing the factors which limit attempts to implement the recommendations. Teachers are frustrated by their text books, by their workload, by the school environment, by parental attitudes, and by the inadequacy of their own preparation in the content area. While the new possibilities for approaches to instruction will not solve all problems, there is reason to believe that research will lead to recommendations on how new technology may aid in implementing the "Agenda for Action." Teachers can be expected to respond positively. The groundwork has been established. Now new ideas are needed on how these recommendations can be implemented. Approaches which make use of microcomputers, video disks, and other equipment offer a vehicle for these new ideas. New applications are so much in demand that they could lead to an acceptance of the vehicle itself.

A list of questions needing investigation in this regard may include the following: Are the roadblocks present in mathematics problem solving? How can computers enhance problem solving for the typical student other than merely programming an algorithm already memorized? What areas are particularly open to interdisciplinary approaches using new information technology? What are situations where individualized instruction is advantageous and how can recent advances in technology be used in such situations? What are factors that prevent some students from successfully using computers? Is there a situation that exists similar to "math anxiety"? How may coordinated approaches toward the teaching of science and mathematics be implemented? Can the computer serve as the common interface?

The "PRISM" report indicates that attention must be given to teacher and parental attitudes toward the purposes of instruction and alternative approaches. Society's view of the teaching profession is a major problem for education today. It is possible that the status of the profession can be improved by using modern day tools in instruction; however, that possibility will be lost if new approaches are forced into unsuitable applications. Research must be conducted to find the areas of application which are suitable and effective and which both teachers and parents will support.

14. The Heavy Paper Work Load for Teachers and Administrators

For a teacher, it is discouraging to see the substantial tools being placed into the hands of managers in business to ease their tasks when the paper work for teachers and administrators continues to grow and no new tools are offered. Industry easily justifies convenient editors for word processing, data management systems, electronic scratch pads for budgeting and scheduling, and other modern tools. Expenditures in this area have led to the development of total packages where all of these functions are menu driven and operate on the same file structure.

Common sense marketing dictates that the cost of developing these packages for education are not justifiable. Otherwise, the packages would exist. One factor which retards development of educational packages is industry's fear that educators are reluctant to use the tools. Again, it is society's image of teachers and principals as being different from small businessmen that obscures the fact that much of the paperwork is similar. Research should be supported to prepare software packages which aid the teacher, the principal, and the superintendent.

More is required for implementation than making specific recommendations regarding the applications of existing software. It also is essential that the cost effectiveness of this approach toward the non-classroom tasks be demonstrated. Some readers may consider this application unimportant and unexciting. To the teacher, however, it is clear that a reduction of the time spent on clerical duties can lead directly to more time spent on teaching task be it preparation of lessons, more carefully graded papers, or clearer communication with parents. An electronic time line capable of updating, among other tasks, may enable supervisors to keep abreast of what is actually being taught and may help the teacher become a better planner. An electronic grade book and absence recorder could be a tremendous timesaver. A text editor would be invaluable in writing tests and student evaluations. For the principal, the applications are many and obvious. Recommendations by experts can clarify which applications are suitable for a microcomputer and which require a minicomputer. More importantly, the availability and cost effectiveness of these tools must be communicated to the local units. It is difficult for a superintendent to justify a large expense for software packages if success is not documented or if no one in the local unit has had first-hand experience with the packages.

Comments

The preceding remarks clearly indicate a strong bias toward the importance of teacher training. Any attempt to make substantial changes in what is taught and how it is taught (should that course be desired) will require a strong base of trained teachers to be successful. The area of technology is a perfect area in which to focus training. Not only can training take place on how to use the technology, but also the technology itself can be used to do the training.

The communication of research results to the classroom teacher is currently haphazard and has small impact in the classroom. The area of the applications of technology to instruction and administration is an ideal vehicle for changing this pattern. If research and innovation which are applicable to the real school environment are supported, teachers will be eager to explore new ideas. If, however, the products of the research are applicable only to the ideal school environment, teachers again will be disappointed by another lost opportunity. The acquisitions of microcomputers by schools over the past three years is testimony to teachers' desires to improve teaching and learning. Equipment was purchased with funds from tight budgets, with little promise of expert support at the local level, with modest access to educational software, and without a true sense of the overall potential of the equipment. These purchases are a response to a need. The impact upon students would be immediate if the results of research led to an organized approach for the use of the equipment, if equipment is integrated into the total school curriculum instead of limited to narrow applications related to the study of programming, if the equipment is the precursor of even more sophisticated teaching tools, and if the equipment is the first step in a determined effort to improve the preparation of teachers. The opportunity before us is unique; the local school districts have taken the first steps even before an organized set of recommendations is established at the national level. The environment for change is real; however, any proposals for change must be predicated on use of equipment in real schools with real students. Administrators recognize the new possibilities and are eager for sound advice on how to take advantage of new technology to benefit education. Advice is also needed on addressing the dangers encountered in placing computers in the schools. Some staff and students suffer from "computer adolescence" -- a tendency to spend time at the computer keyboard instead of attending to required duties. Research in this area may provide answers which teachers need today.

Research efforts can take many forms. Prototype software is essential. Software for training teachers could be modeled on packages industry uses in training employees. Also, prototype applications for the classroom are essential in order to measure the success or failure of the new approaches. Research on the type of equipment best suited for the schools should also be supported.

Conclusion

As many recognize, the opportunity before us is real just as the burden is real. First a broad range of equipment, in addition to microcomputers, is entering school systems and offers opportunities for improving instruction. Second, if the initial uses of the equipment are unsatisfactory in teachers' opinions, future applications of a broader range of equipment, based on more substantial research, will be hindered. This comment deserves attention.

Micros are entering the schools. In some cases this entrance is disorganized and in some cases there is little expertise to support those attempting to use the equipment. The resulting environment is not conducive to success. A significant failure now to live up to teachers' hope for improving instruction could lead to resistance in the future, when attempts are better organized. This is the price which must be paid for technological advances (especially in hardware costs) when they outpace planning by those responsible for the future uses of equipment in the schools. This "bottom up" approach may in the end be a blessing as it is often a precursor for major change.

It is also important to realize that changing how people do their jobs is always a difficult task unless the changes are clearly an improvement. Teachers have an understandable reluctance to use methods in which they do not believe. This is especially true when the methods appear designed for classroom environments which few have experienced or when the methods do not place due emphasis on the motivating role of the teacher. As suggested above, teachers tend to use methods from which they have benefitted. This is a major reason for suggesting that the new approaches using technology be used in the training of teachers.

The reluctance to adopt new methods easily is not limited to teachers. It is not only education that may be failing to take full advantage of these advances. It would appear that education shares many things in common with other businesses, especially in the area of training and serving adults. These shared applications may provide a base for a partnership with industry in funding proposed research. Such cooperation between government and industry is essential for the products of research to have a significant impact in the classroom.

The current situation encourages a skepticism toward the applications and the effects of technology in the schools. Previous unfulfilled promises (film, overheads, television, slides, phonographs) will cause many experienced educators to question the value of more new and untested equipment. They are aware that current research provides few answers that support applications of the new technology. The purpose of this paper is to propose that there be a two-pronged approach: do the fundamental research necessary to find appropriate areas of application, and use the technology to address the need for in-service training of teachers. Of the two areas, the latter is the more important. Both are appropriate for a national role in education. Training teachers and administrators permits decisions to be made at the local level based both on personal experience and research.

One large danger looms ahead if application of the new technology to instruction proves immensely successful. Potentially, such a result could lead to a dramatic improvement in education. Unfortunately, this improvement may occur for only the chosen few. It would be very sad if the gap between the wealthy districts and the poor districts widened due to access to modern equipment.

There are many potential areas of application for the new information technology. The remarks above are intended to initiate discussion. It is important that discussion be based on reality. The schools -- the students, the facilities, and the teachers -- are likely to remain as they are. Technology may help improve the schools, but it would be a mistake to wait for schools to improve before applying that technology.

THE MATHEMATICAL SCIENCES CURRICULUM K-12: WHAT IS STILL FUNDAMENTAL AND WHAT IS NOT

A Report to the National Science Board Commission on
Precollege Education in Mathematics, Science, and Technology
by

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EXECUTIVE SUMMARY

Our charge from the NSB Commission was to identify what parts of mathematics must be considered fundamental for education in the primary and secondary schools. We concluded that the widespread availability of calculators and computers and the increasing reliance of our economy on information processing and transfer are significantly changing the ways in which mathematics is used in our society. To meet these changes we must alter the K-12 curriculum by increasing emphases on topics which are fundamental for these new modes of thought.

This report contains our recommendations on needed changes -- additions, deletions, and increased or decreased emphases -- in the elementary and middle school mathematics curricula and a statement of more general concerns about the secondary school mathematics curriculum.

With regard to elementary and middle school mathematics, in summary, we recommend:

- That calculators and computers be introduced into the mathematics classroom at the earliest grade practicable. Calculators and computers should be utilized to enhance the understanding of arithmetic and geometry as well as the learning of problem-solving.

- That substantially more emphasis be placed on the development of skills in mental arithmetic, estimation, and approximation and that substantially less be placed on paper and pencil execution of the arithmetic operations.

- The direct experience with the collection and analysis of data be provided for in the curriculum to insure that every student becomes familiar with these important processes.

We urge widespread public discussion of the implications of the changing roles of mathematics in society, support of efforts to develop new materials for students and teachers which reflect these changes, and continued and expanded experimentation within the schools.

With regard to the secondary school curriculum, in summary, we recommend:

- That the traditional component of the secondary school curriculum be streamlined to make room for important new topics. The content, emphases, and approaches of courses in algebra, geometry, precalculus, and trigonometry need to be re-examined in light of new computer technologies.

- That discrete mathematics, statistics and probability, and computer science now be regarded as "fundamental" and that appropriate topics and techniques from these subjects be introduced into the curriculum. Computer programming should be included at least for college-bound students.

Modern computer technology clearly has vast potential for enriching and enlivening the secondary school curriculum. However, we are not now in a position to make firm recommendations. There is need for research on the effects of incorporating technology into the traditional secondary school curriculum. We urge Federal support for investigations into this question, including development of experimental materials and prototypes of actual school curricula.

Although we are generally optimistic about the future role of computers, we feel we must highlight one point that worries us even though it is not directly within our charge. The disparity of access between children who have a computer at home and children who do not threatens to widen the educational gap that already exists between different economic strata. It is urgent that programs be designed to address this problem.

We clearly recognize that the most immediate problem is not the mathematics curriculum, but the need for more, and better qualified, mathematics teachers. One section of this report is devoted to recommendations on attracting and training prospective teachers, better utilizing the talents of in-service teachers, and retraining teachers who are inadequately prepared for teaching mathematics. We feel that the coming changes in subject matter and emphasis not only will bring a new sense of vitality to K-12 mathematics, but also will encourage teachers actively to seek and participate in programs of professional development.

The Conference Board of the Mathematical Sciences stands ready to assist efforts to develop immediate strategies for addressing the teacher shortage and to develop long-term strategies for bringing about the curricular changes envisioned in this report.

I. The NSF/CBMS Meeting

In response to suggestions made at the July 9, 1982 meeting of the National Science Board (NSB) Commission on Precollege Education in Mathematics, Science, and Technology, the Conference Board of the Mathematical Sciences (CBMS) held a special meeting to address the topic THE MATHEMATICAL SCIENCES CURRICULUM K-12: WHAT IS STILL FUNDAMENTAL AND WHAT IS NOT. The meeting was held on September 25-26, 1982 at the headquarters of the Mathematical Association of America in Washington, D. C.

Participants in the meeting included the presidents of the American Mathematical Society, National Council of Teachers of Mathematics, Mathematical Association of America, American Mathematical Association of Two-Year Colleges, and Society for Industrial and Applied Mathematics. The other participants included two members of the NSB Commission, two members of the Commission staff, and representatives of the CBMS constituent organizations and the CBMS officers.

II. Recommendations to the Commission

INTRODUCTION

In the limited time available during the conference, it was not possible to establish full consensus on every detail of the working group reports. However, there clearly was broad consensus on the need to incorporate calculators and computers, as well as additional data analysis, into the K-12 curriculum and to make the necessary adjustments in the mathematical topics and modes of thought traditionally taught at these grade levels.

Some detailed recommendations on the fundamentals in the K-8 curriculum, what should be emphasized more and what should be emphasized less, are given in the working group report "Elementary and Middle School Mathematics." The corresponding adjustments needed in the secondary school curriculum, where the impact of technology is even greater, are described in more general terms in the two reports "Traditional Secondary School Mathematics" and in the report "Non-traditional Secondary School Mathematics." In this area much more investigation and experimentation are required before a firm consensus can be reached.

Recommendations on dealing with the challenge of providing children with access to, and understanding of, computers and calculators pervade this entire report. They are dealt with specifically in the report "The Role of Technology." A statement of the relationship between the mathematics curriculum and what is, or can now be, taught in other disciplines is given in the report "Relations to Other Disciplines." The report entitled "Teacher Supply, Education, and Re-education" contains a variety of recommendations on attracting and retaining well-qualified mathematics teachers.

There was general agreement at the conference that the most pressing immediate problem is the need for more, and better qualified, teachers in the classrooms. No curriculum, no matter how well-founded, can possibly succeed without dedicated and competent teachers to teach it. However, many participants felt that appropriate changes in the curriculum at this time, rather than detract from efforts to deal with the teacher shortage, could bring a new sense of vitality to K-12 mathematics and could serve to encourage teachers to actively seek and participate in programs of professional development.

Participants in the conference were also in agreement that their suggestions, even if influential in full, cannot be expected to constitute a "cure-all" for all the shortcomings of K-12 mathematics. In fact, a fundamental improvement in K-12 mathematics can be hoped for only within the framework of a general improvement of the total school environment. Remedies for the difficulties facing the teaching community (low teachers' salaries, low prestige, lack of support by society, lack of discipline in the classroom, irregular attendance, etc.) are societal in nature and fall outside the mandate and the competence of this group.

SOME ADDITIONAL RECOMMENDATIONS

In addition to the concerns and recommendations in the working group reports, a few points were emphasized in the general discussions which are of vital importance in the implementation of any curricular changes:

o Textbooks

Textbooks play a key role in the mathematical sciences curriculum at all levels. Any major changes in the curricula at the elementary, middle, or high school levels must be accompanied by corresponding changes in textbooks. For this to happen, the groups responsible for preparing textbook series and for adopting textbooks must be deeply involved in efforts to update these curricula.

o Testing

To a large extent the grade and high school teachers are under strong pressure to train their pupils so as to maximize their chances of doing well on standardized tests. As long as these tests stress computations, the pupils are bound to be drilled in computations, regardless of any other guidelines the teachers may have received, and even contrary to the sounder convictions the teachers themselves may have.

We call the attention of the Commission to the power and influence of standardized tests. Properly modified, these can have considerable effect in hastening the hoped-for improvements in the present teaching of mathematics in grades K-12.

o Articulation

The entrance requirements and course prerequisites of the nation's colleges and universities are major factors in determining the topics in the secondary school curriculum as well as the amount of time devoted to them. Efforts to change the curriculum at the secondary level must be carried out in a cooperative effort with the colleges and universities.

o Equal Access

The disparity of access to computers between children who have a computer at home and children who do not threatens to widen the educational gap that already exists between different economic strata. It is urgent to design programs to address this problem.

o Women and Minorities

The conference noted with satisfaction the improvement during recent years in the participation of women in upper secondary mathematics. The many efforts that have led to this improvement must continue to be supported. We look forward to corresponding success with minority and handicapped students.

WORKING GROUP REPORT: ELEMENTARY AND MIDDLE SCHOOL MATHEMATICS

Arithmetic, and, more generally, quantitative thought and understanding continue to become more important for more people, but the importance of various aspects of arithmetic has changed and will continue to change as computers and calculators become pervasive in society. The suggestions below are designed to equip students better for life and effective functioning in the developing age of technology. We believe implementation of these suggestions into the K-8 curriculum will make students more adaptive to future change, better equipped to use modern technology, better grounded in the mathematical bases for other sciences, and better grounded for further school mathematics.

A principal theme of K-8 mathematics should be the development of number sense, including the effective use and understanding of numbers in applications as well as in other mathematical contexts.

The changes we propose are fairly substantial, but are primarily in emphasis rather than in overall content. We believe they are consistent with, and are natural outgrowths of, recommendations relative to K-8 education of the earlier valuable documents, Basic Mathematical Skills by NCSM and An Agenda for Action by NCTM.

When implemented, the changes will be only modest at the K-3 level but more significant at the 4-6 and 7-8 grade levels. They essentially replace excess drill in formal paper-and-pencil computations with various procedures to develop better number sense on the part of the student.

Here is a list of various special concerns:

1) Thorough understanding of and facility in one-digit number facts are more important than ever.

2) The selective use by students of calculators and computers should be encouraged, both to help develop concepts and to do many of the tedious computations that previously had to be done using paper and pencil.

3) Informal mental arithmetic should be emphasized at all levels, first aimed at exact answers and later at approximate ones. Such activity is necessary if students are to be able to decide whether computer or calculator printouts or displays are reasonable and/or make sense. Informal mental arithmetic involves finding easy, not formal algorithmic, ways of looking at number relationships.

4) There should be heavy and continuing emphasis on estimation and approximation, not only in the formal round-off procedures, but in developing a feel for numbers. Students need experience in estimating real world quantities as well as in estimating numerical quantities which appear in complicated form. Methods requiring explicit (right or wrong) answers should be used where possible to help develop estimating procedures. For example, many exercises on comparing fractions with easy ones (e.g., 12/25 with 1/2, and 103/299 with 1/3) can be used to get students to think of more complicated fractions as close to, but less than (or more than) easy fractions.

5) There should be a heavy and continuing emphasis on problem-solving, including the use of calculators or computers. Trial and error methods, guessing and guestimating in solving word problems should be actively encouraged at all levels to help students understand both the problems and the use of numbers. Naturally, examples and illustrations should be appropriate to the students' age, interest, and experience.

6) Elementary data analysis, statistics, and probability should be introduced, or expanded in use, including histograms, pie-charts, and scatter diagrams. The understanding and use of data analysis is becoming a vital component of modern life. The collection and analysis of data should

include personal data of meaning to students,(e.g., number of siblings, students' ages,heights and weights), data culled from newspapers, almanacs, and magazines, random data such as that produced by urn schemes and data from experiments in other school subjects.

7) Place value, decimals, percent, and scientific notation become more important. Intuitive understanding of the relative sizes of numbers that arise in the everyday world of applications becomes even more vital.

8) More emphasis on the relationship of numbers to geometry including, for example, number lines and plotting, should lead to better understanding of the concepts of arithmetic and of geometry.

9) Understanding of fractions as numbers, comparison of fractions, and conversions to decimals should have more emphasis while drill on addition, subtraction, and division of fractions with large denominators should have less.

10) Drill on the arithmetic operations on three- (and larger) digit numbers should be de-emphasized. Such computations can and should be done by calculators and computers.

11) Intuitive understanding and use of the mensuration formulas for standard two- and three-dimensional figures should be emphasized. More stress on why the formulas make sense is needed.

12) Function concepts including dynamic models of increasing or decreasing phenomena should be taught. (For more details, see 4) in "Traditional Secondary School Mathematics.")

13) The concepts of sets and some of the language of sets are naturally useful in various mathematical settings and should be used where appropriate. However, sets and set language are useful tools, not end goals, and it is inappropriate to start every year's program with a chapter on sets.

14) Based on motivation from arithmetic, algebraic symbolism and techniques should be encouraged, particularly in grades 7 and 8.

15) More extensive use of mathematics and computers in social science and science courses should be actively pursued. We encourage the consideration of this matter by experts in these fields and welcome opportunities to collaborate on further work in this area.

A discussion of possible computer programming or computer literacy courses is left to other groups for further study.

Implementation Concerns

1) We hope the Commission will encourage widespread public discussion of the implications for K-8 mathematics of the changing roles of arithmetic in society. As an early step, we suggest discussions and conferences between

teachers, supervisors, mathematics educators, mathematicians and editors of textbook series concerning this report and others on the same general topic. Such conferences could be quite inexpensive if most participants are local.

2) We hope the Commission will seek ways to encourage the development and use of student texts and teacher training materials in the spirit of these questions.

3) We hope the Commission will seek ways to encourage change in standardized tests toward number sense and away from single-operation computational skills.

4) We hope the Commission will encourage school systems to reassign interested teachers at the 4-6 grade level to become specialists at teaching mathematics and other disciplines. One mode might be a simple trade of classes between teachers with each teacher concentrating in areas of particular interest and competence. The needed changes in emphasis will be much easier to effect if those actually teaching any subject are selected for their special interests and attitudes. Special inservice training programs should be developed for all such semi-specialized teachers, whatever their subject.

5) We hope the Commission will seek ways to improve the status of teachers and the conditions under which teachers attempt to do the important and difficult job of educating future citizens.

6) We believe that the needed changes can be brought about somewhat gradually and with general support of those concerned. There already is discussion in teacher and supervisor groups concerning many of the ideas put forth here.

The proposed changes generally involve modifications in the way mathematics is introduced and used in schools rather than adding new subject matter. The changes should permeate texts and not just be add-ons that can be ignored. There appears to be an approximate balance in time between topics needing more emphasis and those needing less. With the exception of computer use and the possible exception of parts of data analysis, the topics needing added emphasis have been taught and learned in American schools at various times and places in the past. The diminished role of paper and pencil computation is perhaps the topic which will provoke most concern and possible disagreement.

WORKING GROUP REPORT: TRADITIONAL SECONDARY SCHOOL MATHEMATICS

Current secondary school mathematics curricula are organized into separate year-long courses covering algebra, geometry, and precalculus topics. There are proposals that challenge this traditional division of school mathematics and the position of calculus as the primary goal for able college-bound students. Thus, the following analysis uses conventional course headings for discussion of proposed changes in traditional topics, not as endorsement of the status quo.

1) Overall Recommendation

The traditional component in the secondary curriculum can be streamlined, leaving room for important new topics. However, since breakthroughs in technology which allow this streamlining are so recent and the conceivable implications so revolutionary, it is not yet entirely clear what specific changes are appropriate.

2) Algebra

The basic thrust in Algebra I and II has been to give students moderate technical facility. When given a problem situation, they should recognize what basic algebraic forms they have and know how to transform them into other forms which might yield more information. In the future, students (and adults) may not have to do much algebraic manipulation -- software like mu-Math will do it for them -- but they will still need to recognize which forms they have and which they want. They will also need to understand something about why algebraic manipulation works, the logic behind it. In the past, such recognition skills and conceptual understanding have been learned as a by-product of manipulative drill, if learned at all. The challenge now is to teach these skills and understanding even better while using the power of machines to avoid large time allotments to tedious drill. Some blocks of traditional drill can surely be curtailed, e.g., numerical calculations using look-up and interpolation from logarithm and trigonometry tables.

3) Geometry

A primary goal of the traditional Euclidean geometry course is to develop logical thinking abilities. But not every fact need be given a rigorous proof to pursue this goal. Nor need this be the only goal of geometry, nor geometry the only means towards this goal.

We recommend that classes work through short sequences of rigorously-developed material, playing down column proofs, which mathematicians do not use. These proof sequences should be preceded by some study of logic itself. Important theorems not proved can still be explained and given plausibility arguments, and problems involving them can be assigned. The time which becomes available because proofs are de-emphasized can be devoted to study of algebraic methods in geometry, analytic geometry and vector algebra, especially in three dimensions. Work in three dimensions is essential if one is to develop any pictorial sense of relations between many variables, and handling many variables is essential if one is to model phenomena realistically.

There is much room for using computers in geometry. The power of graphics packages makes it much easier for students to get a visual sense of geometric concepts and transformations. The need to use algebraic descriptions of geometric objects when writing graphics programs reinforces analytic geometry. Finally, the algorithmic thinking needed to write programs bears much resemblance to the thinking required to devise proofs.

4) Precalculus

What often happens in this course is that students see the same topics yet another time, with more drill but with little new perspective. For better students there may not be a need for a precalculus course if drill is no longer so important and if algebra and geometry are done "right," with the concepts made clear. For instance, one justification for the precalculus course is the perceived need to develop the idea of functions; functions appear in Algebra I and earlier, but current teaching may give too static an understanding. With computers, the concept of function can be made central earlier and more clearly. The computer supports qualitative analysis of the graphs of functions, in a dynamic mode of display, and also allows detailed analysis of zeros, rates of change, maxima/minima, etc.

5) Algorithmics

Computers and programming have made the creative human talents and skills involved in developing and analyzing algorithms extremely important. These talents and skills, emphasized by the group on nontraditional topics, can be exercised quite naturally through traditional topics as well. Much of high school algebra consists of systematic methods for handling certain problems, e.g., factoring polynomials. Such methods are algorithms. Instead of making the student carry out such methods with paper and pencil a boring number of times, have the student do it just a few times and then program a computer to do it. The understanding gained should be at least as great.

6) The Average Student

For the many students in secondary school who are not specially talented in mathematics and not headed for careers in science or technology, current programs are a source of discouragement, anxiety and repetition in a dull "basic skills" program which serves them poorly. We cannot ignore the needs of this large and important group. Computers, as mathematical tools and media of instruction, offer a fresh window into mathematics for them.

7) Cautions

We have suggested that technology provides an opportunity to devote less time to traditional techniques while boosting understanding and allowing more time for more complex, realistic problem-solving. However, there are several cautions. First there are widespread and deep reservations about how much traditional goals should give way to technology. Second, there is little research data on the feasibility of such changes, and there are almost no prototype school curricula embodying the new priorities. Experimental programs, and research on the results, must be given major support. Third, changes in secondary programs must be carefully articulated with the expectations of colleges and employers, who often have conservative views about curricula. Finally, the syllabi of an extensive range of standardized tests play a very influential role in setting curricula and the actual classroom emphases of teachers. If curricula are to change, the tests must be changed. Clearly, strong national leadership and cooperation are necessary, from teachers, mathematicians and public policy-makers, to meet these challenges and implement significant change.

WORKING GROUP REPORT: NON-TRADITIONAL SECONDARY SCHOOL MATHEMATICS

On two basic principles the panel was unanimous:

- There is need for substantial change in both the subject matter of and the approach to teaching in secondary school mathematics.

- If changes are to be made in secondary school mathematics, we must make haste slowly, taking care at all times to insure full consultation with and support from the secondary school mathematics teaching community.

Our specific recommendations are grouped under five headings: Subject Matter, Approach to Teaching, The Use of New Technology, Teacher Training and Implementation.

1) Subject Matter

Careful study is needed of what is and what is not fundamental in the current curriculum. Our belief is that a number of topics should be introduced into the secondary school curriculum and that all of these are more important than, say, what is now taught in trigonometry beyond the definition of the trigonometric functions themselves. These topics include discrete mathematics (e.g., basic combinatorics, graph theory and discrete probability), elementary statistics (e.g., data analysis, interpretation of tables, graphs, surveys, sampling) and computer science (e.g., programming, introduction to algorithms, iteration).

2) Approach to Subject Matter

The development of computer science as well as computer technology suggests new approaches to the teaching of all mathematics in which emphasis should be on:

- algorithmic thinking as an essential part of problem-solving

- student data gathering and investigation of mathematical ideas in order to facilitate learning mathematics by discovery.

3) Technology

New computer technology allows not only the introduction of pertinent new material into the curriculum and new ways to teach traditional mathematics but it also casts doubt on the importance of some of the traditional curricula, just as the hand calculator casts similar doubts about instruction in arithmetic. Particularly noteworthy in this context at the secondary level are:

- Symbolic manipulation systems which even now, but certainly far more in the near future, will allow students to do symbolic algebra (and calculus) at a far more sophisticated level than they can be expected to do with pencil and paper.

- Computer graphics and the coming videodisc systems which will enable the presentation and manipulation of geometric and numerical objects in ways which should be usable to enhance the presentation of much secondary school mathematical material.

One caveat which we would stress is that this technology and related software packages must be used not to enable students to avoid understanding of the essential mathematics but rather to enhance such understanding and to allow creative experimentation and discovery by students as well as to reduce the need for tedious computation and manipulation.

4) Teacher Training

There are two aspects of this:

a) Retraining of current teachers in the new topics, approaches and technology. One possible new approach to this might be the use of college students to aid and instruct secondary school personnel as part-time employees and perhaps through such incentives as forgiveness of student loans.

b) Education of new teachers

Crucial to long-term solution of the secondary school mathematics education problem is that the requirements for degrees in mathematics education be, as necessary, changed to incorporate modern content and approaches. In particular, we believe that all prospective teachers of secondary school mathematics should be required to take at least:

- one year of discrete mathematics in addition to traditional calculus requirements

- one semester or one year of statistics (with focus on statistical methods rather than mathematical statistics)

- one year of computer science.

5) Implementation

We recognize that the kinds of changes proposed here not only require much more study than has been possible by our panel but that also they will never be implemented unless there is dedicated cooperation among:

- secondary school teachers of mathematics and their professional organizations

- college curriculum people in schools of education and in mathematics departments and including their organizations

- state and local education authorities and their organizations.

A conference at an early date bringing together these groups to discuss the relevant problems and plan future action might be the most fruitful next step to provide some momentum for the changes we believe are necessary.

WORKING GROUP REPORT: THE ROLE OF TECHNOLOGY

Computers and related electronic technology are now fundamental features of all learning and working environments. Students should be exposed to and utilize this technology in all aspects of school experience where these devices can play a significant role.

We recommend:

1) The potential of technology for enhancing the teaching of mathematics and many other subjects is vast. Development of such resources should be supported at a national level. Specific examples include computer-generated graphics, simulations, and video-disc courseware materials. There should be efforts to create a network providing easy access to such banks of material.

2) While computing technology offers promise to enhance learning, differential access to the benefits of that technology could widen the gaps in educational opportunity which already separate groups in our society. It is imperative that every effort be made to provide access to computers and their educational potential for all sectors of society.

3) As a general principle, each mathematics classroom should have available computers and other related electronic technological devices to facilitate the computing and instruction required for mathematics learning and competency. Such availability of computers and other electronic technological devices in the mathematics classroom is as important as the availability of laboratory equipment for science instruction.

4) Hand calculators should be available in mathematics classrooms (both in elementary and secondary schools) for students on the same basis that textbooks are now provided.

5) Support should be given for broad developments in software that may be useful in the schools. School districts should encourage their teachers and students to engage in cooperative development activities and to find ways to recognize and disseminate the products of those efforts.

6) Computer literacy involves not only the use of computers to accomplish a great spectrum of tasks but also a general understanding of the capabilities and limitation of computers and their significance for the structure of our society. Development and implementation of appropriate programs to teach these more general concepts should be supported.

7) Possible structural changes emanating from technological changes will require careful study and deliberations over a long period of time. This activity must be encouraged and supported from a national level. The exploratory projects bring together teachers, curriculum developers, mathematicians, and affected interested parties from business and industry. The

new programs developed should be tested extensively in a variety of settings to insure that they work with real students and schools before extensive implementation is attempted.

8) The interplay between word-processing, computers, data bases, and data analysis methods assist in breaking down barriers between disciplines thus offering an opportunity for schools to provide a range of holistic problem-solving experiences not typical in school today. Using the technology as an aid, students can plan and conduct data collection, analysis, and report writing that is realistic, attractive, and far beyond normal expectations in today's schools.

9) The need for well-trained, highly qualified teachers of mathematics is a must in a technological society. Support should be given to organizing programs for inservice training and retraining of current teachers of mathematics (elementary and secondary) who are inadequately prepared to teach a technologically-oriented curriculum, but have the capacity to profit from such programs to strengthen their mathematical preparation and teaching skills.

10) While technology provides opportunity, it also makes demands. The world becomes a more complex place in which to live. If we are to insure that a broad spectrum of society can function and participate actively in the business/industrial community and decision-making of the country, it is imperative that students become adept in the precise, systematic, logical thinking that mathematics requires.

WORKING GROUP REPORT: RELATIONS TO OTHER DISCIPLINES

As this group has considered the effect of (computational) technology on the mathematics curriculum and the need to revise this curriculum in the light of this expanding technology, it is also necessary to consider the effect of this technology and the proposed curriculum changes on "other disciplines." We have interpreted the phrase "other disciplines" rather broadly.

First, using a narrow view, and thinking in terms of "academic disciplines", we must look at the effects these curriculum changes will have on science education. There has always been a necessary interaction between the science and mathematics curricula. In the case of the high schools where the disciplines tend to be separated and segregated, there has always been a necessary coordination of syllabi and curricula, particularly with the educational programs in the physical sciences. At a minimum, this revised curriculum, which encourages a good [illegible] of estimation, provid[illegible] an opportunity for elementary and high s[illegible] education to be more re[illegible] and eliminate the use of specialized problems with "easy numbers." If we raise our sights a bit, this approach to the mathematics curriculum provides an opportunity for a better coordinated and integrated total science education. Furthermore, the introduction of statistical ideas, data handling procedures, and discrete mathematics provide an opportunity for a more mathematical discussion of social sciences programs at the elementary and high school levels. Similarly, changes in currently available tools will undoubtedly affect courses in "business" and commercial programs.

Related questions arise on the other side. What do the school programs and the college programs in natural sciences, social sciences, and business expect or desire in the mathematical preparation of entering students? We believe the suggested curriculum can only be an improvement, but discussion with leaders of those disciplines are required.

Taking the broad view, we also believe that this modified curriculum, which provides students with the same (or greater) ability to use mathematics as well as an ability to use and appreciate the technology, will provide for a wiser citizenry. The graduates of such a program should be better equipped to deal with "poll results" and statistical data references to the economy and sociological problems.

We believe there is one serious area in which the nation needs more data for the development of an appropriate mathematics curriculum. Namely, what are the needs, in terms of mathematical skills, of the students who seek technical vocational employment without going on to further schooling? What are the needs of students going on to technical or vocational schools? Nevertheless, we believe the new curriculum will do at least as good a job as the existing one. A conference or meeting to explore this area would be an excellent idea and complement our work.

WORKING GROUP REPORT: TEACHER SUPPLY, EDUCATION AND RE-EDUCATION

Efforts to improve and up-date the mathematics curriculum and to increase the mathematics, science, and technology literacy of all citizens require the support of qualified mathematics teachers at all levels. At present there is a serious and well-documented shortage of teachers of mathematics at the elementary and secondary school levels in many areas of the country. Economic, employment, and social conditions forecast that the current short supply may indeed be a long-term problem. Furthermore, even in geographic locations where adequate supplies exist the frequent turnover of mathematics teachers tends to impede learning.

The following recommendations address the need to increase the supply of mathematics teachers as well as improve the quality of the teaching and thereby the learning of mathematics:

1) While state and local efforts by industry, business, and academia to deal with the teacher shortage are laudable, and should continue, the magnitude of the problem is national in scope. An articulated national commitment with federal leadership and support is needed for its resolution. The public should be made aware of the problem through more effective publicity.

2) Incentives of all types need to be studied to attract and retain qualified teachers of mathematics. Financial incentives should be given special attention with priority assigned to those which do not create undue inequities and tensions among colleagues in order to avoid being counter-productive. Examples of following incentives and support systems include the following:

a) Forgiveness on student loans or interest on loans for those who enter the teaching field
b) Higher entry level salaries for those with special expertise (e.g., computer training)
c) Reduced teaching loads to allow mathematics teachers to pursue graduate studies or other advanced training in mathematical sciences and applied areas
d) Financial support for graduate study or other advanced training in mathematical sciences and applied areas
e) Salary differentials by discipline
f) Summer positions and other cooperative arrangements with business and industry to supplement a teachers income (with the obvious caveat that the short supply of teachers is largely due to the fact that higher industrial salaries lure teachers away; industry would have to be discouraged from using this arrangement for recruitment purposes).

3) In an era when content and technology are changing so rapidly incentives are needed to keep qualified teachers in the field abreast of current trends in the mathematical sciences. Inservice workshops, NSF-type institutes, retraining courses, industrial experiences, and other forms of continuing education can serve to refresh the faculty and renew their commitment to teaching.

4) In some parts of the country, teachers from other disciplines are being assigned to teach mathematics classes. These teachers need special subject matter training and assistance in developing appropriate teaching strategies in order to succeed in their new assignments.

5) Encouraging colleges and universities to loan their faculty and business and industry to loan their mathematically-oriented employees to teach courses in the secondary schools could be mutually beneficial. Qualified retirees or near retirees might also be recruited to enter the teaching field. Exposing college and university teachers to the high school experience might be enlightening and beneficial for them. (Of course, the issues of appropriate teacher training and certification need to be addressed.)

6) In states where this is not the norm, it is recommended that teacher certification requirements be stated in terms of specific topics to be covered in the subject area rather than in terms of just total number of credits.

7) Recommendations regarding the mathematical fundamentals to be covered in educating qualified teachers of mathematics include:

a) Elementary level

It is strongly suggested that mathematics at the elementary school level be taught by teachers who specialize in mathematics. Whether the teacher specializing in mathematics should be assigned to all grades or just to grades 4-6 (or 4-8) requires further study. An alternative approach would be to identify those teachers in a given school who most enjoy teaching mathematics. Those teachers could be assigned to teach all mathematics courses across a grade level, while other teachers do similarly in reading and writing.

The following recommendations pertain to both the regular elementary school teacher and the teacher specializing in mathematics:

For entry into the mathematics education program for elementary school teachers, at least three years of college-track mathematics in high school are recommended. College mathematics courses should provide a sufficient background to understand the relationships between algebra and geometry, functions, elementary probability and statistics, instruction in the use of a hand-held calculator, and some exposure to computers. Creative approaches to problem-solving should also be included in the curriculum. Training should be at least a level above what is being taught. This background is particularly important in light of children's awareness of the world around them through television, other media, computers, and so on.

b) Secondary level

Secondary school mathematics teachers should have course work in mathematics equivalent to a major in mathematics. Requirements for those who will teach mathematics should include the equivalent of a two-year calculus and linear algebra sequence, discrete mathematics, probability and statistics, and appropriate computer training. These courses should develop in the student a sense of "mathematical maturity" in the approach to problem-solving.

Note: College and university curricula for educating mathematics teachers should be re-examined and revised in accordance with the above guidelines and goals. Contingency plans should be developed in case separate departments of mathematics and computer science are established at the secondary level in the future.

III. Conclusion

The recommendations cited here require careful planning and implementation. With high technology a mainstay of our present and future society, it is imperative that we recognize and promote mathematics as a powerful, useful, and enjoyable component of our lives.

INSTRUCTION FOR DEVELOPMENT OF UNDERSTANDING

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PREFACE

Although there are many important aspects of instruction which might have been included in this paper, I have chosen to focus on Instruction for the Development of Understanding. In my opinion, when students understand ideas, they are more literate about scientific language and ideas; they are better able to solve problems which involve scientific ideas; they are better able to reason about the natural world; they are more likely to value the scientific ways of knowing; they are more comfortable about the world around them. Whatever our reasons for studying science, I believe they are enhanced by a better understanding of the ideas of science and of the processes by which those ideas are developed.

Existence of Initial Conceptions

Research suggests that students enter science classes with their own ideas about the world.[1,2,3,4] Often they are unable to articulate their mental framework, but when confronted with a situation, they will make, with considerable conviction, a prediction of what will happen in the situation. One might think that these are unreasoned guesses, yet responses made by introductory physics students bear a similarity in terms of both the predictions themselves and the reasoning used to support these predictions. Large proportions of entering physics students believe, for example, that stationary, rigid objects do not exert forces; that a constant unbalanced force is required to keep an object moving with a constant velocity; that components of motion in two directions (e.g., vertical and horizontal) are not independent; that heavier objects fall faster; that images are located on the surfaces of mirrors; that the temperature of ice is always 32°F; that the earth's shadow causes the crescent phase of the moon; and that air pressure causes gravity. All of these views have some basis in prior experience. I refer to these initial conceptions as "alternative conceptions," because they are alternative to the current view of science.

Many alternative conceptions not only appear as students make predictions about what will happen in a particular situation, they also are revealed when students describe representations of the natural world. A careful analysis of errors made in interpreting graphs has revealed that some students confuse the line on a position versus time line graph with the actual path of travel. A graph which is concave downward, for example, is not interpreted as representing slowing down or a possible change in direction but rather a veering to the right along a curved path. Many students interpret the intersection of two velocity vs time graphs to mean that the two objects have the same position.[4]

These alternative conceptions have significance for how we use representatives in science classes.

Alternative conceptions exist before students enter the science classroom and some develop early in the instruction. Students may begin to organize a new set of phenomena through analogical reasoning. Often the analog which they have selected does not adequately represent the entire set of phenomena. For example, after manipulating and observing several combinations of bulbs in series and in parallel circuits, students may conclude that what they have seen can be represented by water flowing through pipes with sprinklers taking the role of the bulbs. While there is some similarity between the flow of electricity and the flow of water, this common analog is inadequate. It is an alternative to the present understanding of resistance and flow in a circuit.

The existence of these alternative conceptions has direct implications for our instruction. Much of the present instructional materials and techniques reflect the assumption that students enter science classes with minds like blank slates. We have often begun to cover these slates with new ideas without acknowledging that there are alternative conceptions already upon them. Philosophers from the past (Socrates, Galileo, Dewey, and Piaget among them) have advocated that teachers begin with students' present understandings and guide development from there. This is my position also. This paper presents a style of instruction aimed at the development of understanding which acknowledges the existence of initial alternative conceptions.

Engagement of Initial Conceptions

If the instruction is to take into consideration the initial conceptions which the students have, one must begin by drawing these ideas from the students. One specific way to learn about students' conceptions is to present the students with a situation which has been known from past classroom experience to elicit a variety of responses. Describe the situation and ask them for their predictions and how they arrived at those predictions.

For example, in the context of gravity, I ask my students, "If a wooden ball and a metal ball (same size but about five times as heavy) are dropped from the same height, which will reach the floor sooner? How will the times of fall compare?" I find that about one quarter of my students respond with the prediction that the heavier ball will take less time; many say it will take about one-fifth of the time of the wooden ball, an answer consistent with that of Aristotle. After making this prediction, these students are generally surprised when they observe the two balls falling together and making one sound when they hit the floor. When the students consider their own ideas in the light of this concrete evidence, they are likely to reconsider their initial thinking and search for a more consistent conception.

Another technique is to ask students to explain an observation they've made. For example, "You've seen a crescent shaped moon. What causes the dark part of this phase of the moon?" The response of nearly half of my students is that the earth causes the shadow on the face of the moon and that it occurs when the moon and sun are on opposite sides of the earth (a situation the scientist calls an eclipse).

At times the experience of participating in a show of hands will require students to make a commitment to one point of view or another and, as a result, heighten the students' readiness for conceptual change. For example, prior to a demonstration discussion of forces on static objects, I have asked students to consider a book on a table. I ask how many believe the table exerts an upward force and how many believe the table does not. Approximately 50% of the students "voted" for each alternative. On this issue, there were bright, articulate students on both sides and the stage was set for a lively discussion.5/

All of these techniques have a common goal, to encourage students to verbalize their initial understanding and to have them record the understanding in writing or publicly so they have made some commitment to it. Making this commitment involves them immediately in the learning process. It engages their thought structure. Their alternative conceptions have served them well; they have allowed them to make predictions or explanations. It requires a convincing, concrete experience which conflicts with their conceptions before the initial thinking will be modified or replaced. Without raising the initial conception to an awareness or commitment level, it is possible for students to fail to recognize the conflict between new evidence and their primitive understandings. Unless students' present understandings are explored, new experiences can be learned context in which they are presented, but students may rely on their old framework when presented with a related situation in a different context.

Direct, First-hand Experience

In the development of understanding, it is particularly important to have early observational experiences relate to the initial conceptions which have been articulated by students. This provides students with an opportunity to determine whether their initial ideas (recently raised to awareness) are adequate and consistent in terms of explaining the new phenomena. Students' interest is already heightened when there is a lack of consensus in the class. They are ready to explore and resolve their conflicting positions. In the case of the gravity example, I drop objects of different materials, shapes, sizes, colors (?), etc., and observe the results. For the crescent moon, I ask students to record their observations the next time they see a crescent phase, also observe and record the location of the sun. Hypothesizing the existence of an upward force exerted by the table seems more reasonable after experiences of hands and springs supporting books and after observing the sagging of a table under a heavy weight.

The sequencing of activities can have a profound effect. Earlier experiences which relate to initial conceptions should be as concrete and directly related to observations as possible. More abstract experiences should come later. This may sound like familiar advice, but in some cases it can mean breaking with the traditional order of curriculum. For example, most physics instruction dealing with forces on moving objects begins with an object moving at a constant velocity (applying Newton's First Law) and proceeds to the accelerating case (Newton's Second Law). The development of my students' understanding has been enhanced by reversing the order. Using a spring scale and a cart, students can record data related to the motion of the cart, and readily experience that a constant unbalanced force produces constant acceleration. They are then ready for a logical argument (constant velocity can't be explained by a constant unbalanced force, an increasing unbalanced force, or a decreasing unbalanced force, therefore...) to show that a constant velocity can be explained by requiring no unbalanced force. It is my experience that students are prepared to accept and understand that there can be constant velocity without an unbalanced force once they have experienced the effect of a constant unbalanced force on an object; the abstract following the concrete experience.[6/]

Interaction Between Experience and Alternative Conception

When students realize that evidence from their experience is in conflict with their existing ideas, they often are ready for the development of a new understanding. They are more willing to reconsider their alternative ideas and perhaps alter them or reject them in favor of an idea more consistent with the experience.

In some cases, the phenomena of the first-hand experiences are themselves compelling enough to suggest a need for resolution of differences. For example, if the students' initial idea is that heavy objects fall in times inversely proportional to their weight, when they experience objects falling together, they recognize the discrepancy with their prediction and are ready to use some help resolving the conflict.

In other cases, the students need to have the discrepancy between their ideas and their experience pointed out to them. Consider those students who believe the earth's shadow caused the dark part of the crescent phase of the moon. Many of them went on to make and record elaborate observations of the moon and sun positions at various times for a month or two. It wasn't until I pointed out to them that they had recorded observations of the crescent moon during the midday while the sun was also high in the sky that they perceived a discrepancy between their explanation and their observations. "How could the earth cast that shadow when the sun and moon are clearly not on opposite sides of the earth?" They knew their original ideas, and they knew the observations they had made, but without the encouragement to note the discrepancy, they may never have paid attention to it. Now, however, they were ready to attempt to come up with an explanation for the crescent moon that would explain the observations.

I might note that while many people require a forced interaction like the preceeding, others recognize the discrepancy more readily. It is as though they carry their conceptions at a higher awareness level.

Perhaps the most difficult pre-conceptions to affect are those which cannot be shown "wrong" merely by noting discrepancy between observations and initial conception. The concept of force is such an example. With the book on the table, there is no way to "see" the table exert an upward force. With these sorts of abstract conceptions, the encouragement of rational thought about a variety of first-hand experiences is necessary and particularly important. For example, it was only after the muscular experience of pushing upward to support a book on the outstretched hand and noting that the effect in all the static object cases was the same, i.e., in each case the object was at rest, then the students began seeking a consistent way to explain the same outcome for various situations. "If my hand exerts an upward force to support the book, I guess the table must do so as well, because they both give the same result."5/

Another difficult teaching situation is when concrete observations can be made to challenge the initial conception, but the procedure in the experience is quite elaborate. The students need careful guidance so that they are clear about the purpose and conclusion of the experiment. They may need to review proportional reasoning so that they understand the meaning of the data they have obtained. When the experience is completed, and the data analyzed, there needs to be an opportunity to consider whether the results were consistent with their ideas before the experiment, and if not, how might they begin to resolve any discrepancies.

There are various ways to encourage students to evaluate the results of an experience in light of their beginning conceptions. A discussion with fellow students, a presentation by the teacher, or reading from a text can help tie together their learnings. I prefer class discussions because they actively engage students in the resolution process. Once a consensus is reached, the process is still not complete. The new idea needs to be tested to ensure that it does account for all of the observations which have been made. Students need to conclude for themselves that the new idea can account for their earlier experiences as well as the latest classroom experience, that it is worthy of replacing their initial conception.

Building a Conceptual Network

Even the invention of a new conceptual idea to account for an experience will not necessarily generate a permanent change in understanding. Two other instructional strategies can help. First, it appears that lasting change involves change in a network of related concepts. For example, in an activity that focused on the arrangement of forces that would keep an object stationary, my instructional goal was to have the students conclude that for each force in one direction, there was a force in the other direction to balance it (i.e., the vector sum of the forces would be zero). In the context of a book at rest on the table, it was necessary to discuss the nature of force and more specifically how each force could be caused. Ideas that the students wanted to discuss included the nature of gravity, air pressure, friction, the nature of rigid bodies, animate versus inanimate objects, and active versus passive actions.

After a lenghty discussion involving all of these ideas, most students were prepared to believe that the table exerted an upward force equal in magnitude to that of gravity.5/ Those who were not quite ready to believe this, at least were willing to consider balanced forces as a tentative way of explaining the "at rest" condition of an object. A willingness to adopt the idea of a table exerting force seemed to depend on small changes in understanding of several other concepts as well.

A second factor which enhances lasting conceptual change is the extension of a concept into other contexts in subsequent lessons or units. For example, in the context of circular motion, it appears useful to revisit some of the arguments used in generating the idea of inertia. "When an object is travelling in circular motion at a constant speed, is it necessary to have a 'forward' force? a force away from the center of the circle? a force toward the center of the circle? Under the influence of each of these forces, what would be the resulting motion?" Earlier while developing ideas about forces on moving objects, our introductory physics students could understand, and even suggested the logical conclusion, that no unbalanced force is necessary to keep an object moving with a constant velocity. They could even use it in most other situations involving straight line motion, but the power and long term understanding was enhanced by repeatedly facing new situations, new contexts, having to explain them, and coming to one's own realization that no forward, unbalanced force was necessary to explain circular motion, projectile motion, or constant velocity against resistive forces, etc. Our results show that when ideas and arguments developed by the class during early discussions are used to help develop other ideas in subsequent units, then those ideas and arguments take on more lasting meaning.

POSTSCRIPT

In preparation for this conference, I was asked to characterize ideal science instruction from my point of view. Realizing that I could not cover every attribute of science instruction, I chose to concentrate on describing instruction which will promote the development of understanding of ideas. By acknowledging the existence of alternative conceptions, by identifying and engaging students' initial ideas, by giving them first-hand concrete experiences to challenge or reinforce their understanding, by comparing their beginning ideas with their recent observations, and by extending new ideas into a network of other developing ideas and other contexts, then we can help students learn and retain the ideas and processes for developing ideas in science. If we can change students' understanding to a level more consistent with the phenomena of the natural world, then we have achieved a major goal of any science class.

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READING RESEARCH AND READING PRACTICE

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There will be three parts to this paper. First, I will summarize major ideas about the process of reading that have emerged from research. Second, I will discuss problems with education that undermine the quality of the reading instruction that children in this nation receive. Finally, and more briefly since this was not my specific charge, I will comment on how computer technology might be used to capitalize on what we have learned is fundamental in the reading process and to ameliorate the problems in current school reading programs.

Nature of the Reading Process

I suppose that there is one point upon which the lay public, the professional educator, and the cognitive scientist are in complete agreement, namely that reading is--or ought to be--a generalizable or transferable skill. Where the public's view falls down is in the assumption that what gives reading skill its generalizability is understanding of letter-sound correspondences. From this assumption comes the conviction that the major emphasis in reading research ought to be to see how phonics works and the major emphasis in reading instruction ought to be on getting phonics across to our youngsters.

Please be clear that the public is not entirely wrong about phonics. Research leaves no doubt that good readers have a facile understanding of the relationships between print, sounds, and meanings whereas lack of understanding of these relationships is a most notable shortcoming of most poor readers (see Perfetti & Lesgold, 1977). The preponderance of evidence from instructional research favors direct instruction in phonics as a part of the beginning reading program (see Pflaum, Walberg, Karegiances, and Rasher, 1980; Williams, 1982).

The problem with the preoccupation that some segments of the public have with phonics is that the view is too limited. In the words of S. J. Samuels, 1982, p. 17, "the development of automatic decoding is but a single factor among many factors which influence comprehension and cannot carry the entire burden and responsibility for ensuring skilled reading. Accuracy and speed of decoding are necessary but not sufficient conditions for good comprehension." Beyond decoding there are at least three other requirements for a high level of reading comprehension.

The first is that the reader possess the organized knowledge, or schema, presupposed by the text. Consider, for instance, a chapter from an elementary school geography textbook. It is very likely to simply presuppose the knowledge that a country is a political subdivision, that countries have different kinds of governments, that countries have locations on the surface of the earth that can be characterized in various ways, that countries have climates and economies, that climates and economies interact, that countries have histories and cultures, and so on. A deep knowledge of any of the concepts that are part of geography would in turn entail a large infrastructure of supporting knowledge.

So, young readers who are able to translate correctly the printed symbols on the pages of a geography textbook still will not be able to understand the material unless they possess the prerequisite knowledge. Evidence has accumulated that the schema embodying what a person knows about a topic is one of the principal determiners of how much he or she will comprehend or learn from new material on this topic (Adams & Bruce, 1980; Anderson, 1983).

Questions about how schemas are organized and the specific manner in which schemas facilitate reading are currently receiving active attention from researchers in several disciplines. For example, there is a growing body of research on the structured knowledge required to understand simple stories of the sort found in basal readers. Formal representations of "story schemas" have been proposed, subjected to empirical test, criticized, and refined (see Stein & Trabasso, 1983).

Schema theory has strong implications for reading and reading instruction. The most general one is that it is a mistake to make narrowly linguistic assumptions about reading. Any knowledge a child might acquire could eventually help that child understand some text or other. A curriculum empty of anything but drill on words and grammar is likely to produce empty, noncomprehending readers.

Schema theory also has a number of specific implications for curriculum and instructions. Young children and less able children of every age frequently do not possess the knowledge presupposed by authors of texts they are expected to read. More newsworthy, even when they do possess the needed knowledge, they often do not activate it and bring it to bear; that is, they tend not to reason about texts in the light of what they already know (Owings, Petersen, Bransford, Morris & Stein, 1980).

Instructional research has demonstrated that there are straightforward procedures that will help young and less able children use what they know while reading. For instance, children who get a regimen of discussion relating what they know to an upcoming reading selection schema activating discussions, if you will--show general benefits in reading new texts (Hansen, 1982).

My second major theme is that proficient reading requires command of strategies, tactics, and procedures. Of course, procedures are part of knowledge in every domain and such procedural knowledge may be required for reading comprehension. For instance, knowing how to take blood pressure may be required for an understanding of a medical text and knowing how to execute a squeeze play may be required for an understanding of a baseball story.

Of general importance for reading is a class of mental procedures for which the term metacognition has been coined. "Metacognition" means knowledge about how one's mind works. A substantial body of evidence indicates that insight into the workings of the mind, how to use the mind efficiently when reading, and what to do when the mind fails to work well are critical to skilled reading. It is well-known that many children who do not have problems with primary school narratives, experience breakdowns later when they must try to learn from science and social studies textbooks. A closer look indicates that one reason for this is that such children do not understand that reading entails management of their own cognitive resources. They are not planful; they do not get clear on the goals for reading; they do not monitor progress in reaching these goals; they do not engage in mental review to assay whether information they are supposed to be getting is still held in memory (Brown, Bransford, Ferrara, Campione, 1983).

Instructional research indicates that direct instruction in metacognitive strategies can lead to generalized improvement in reading comprehension. Notably, Palincsar (1983) has developed a technique called "reciprocal teaching," an important part of which is having a teacher and children alternate roles in asking and answering good questions about sections of text. Apparently the children learn to think about what the important questions are as they read and to monitor their comprehension in terms of whether they are able to answer these questions. Reciprocal teaching has produced excellent results with middle school students whose word identification skills are satisfactory but who lag a couple of years behind their agemates in reading comprehension. Especially significant is the fact that the children show improved performance in science and social studies class when the special teacher and environment are not present.

The third big theme that has been supported by recent research is that good readers are fluent readers. The theory to explain why fluency is important is that when a process has been very well-learned it becomes automatic and can be done with little or no attention. People's attention capacity is limited. Thus, the more automatic each process in reading the better; the attention saved on one process can be invested in another. The hypothesis is, for instance, that a child who is fast and accurate at word identification will have more capacity available to reason about the flow of argument in a text whereas the child who is laboriously sounding out words letter by letter and syllable by syllable--even when the words eventually are identified correctly--will have little capacity left to deal with the text's meaning.

Research on automaticity has dealt with the lowest-level processes in reading, identifying words and bringing to mind their meanings; however, it is a plausible conjecture that the principle applies to higher level processes in reading as well (Samuels, 1982).

In summary, research of the last decade suggests that for a high level of reading comprehension, the reader must have a schema that can serve as the framework for understanding and assimilating the information in the text, must have metacognitive strategies for managing the processes that give birth to understanding [illegible] learning, and must have mastered component probirth to understanding and learning, and must have mastered component processes to a high level of automaticity so that attention bottlenecks do not cause comprehension breakdowns.

Status of School Reading Programs

I will discuss four problems that give cause for alarm about the quality of school reading programs. The first is the precipitous declin over the last decade in the talent of teachers.

At the University of Illinois a decade ago the students choosing education as a major ranked just behind the students electing engineering in terms of high school grades and college entrance examinations. In recent years the average for students electing education has not been far above the minimum that the University of Illinois will accept. The experience at Illinois is mirrored at every education department in the country.

And the story gets worse. A recent article by Kerr (1983) summarizes evidence indicating that talented people continue to leave teaching at every stage: Among undergraduates who initially elect an education curriculum, those who remain are less able than those who switch majors. Among graduates who get a teaching certificate, those who search for a teaching job are less able than those who do not. Among those who are interviewed for teaching positions, candidates who get jobs are less able than candidates who do not. (Whether this happens because of further self-selection on the part of the candidates, or ineptness on the part of school administrators, no one seems to know.) Among candidates who get teaching jobs, those who remain in teaching for five years are less able than those who leave for careers in other fields.

The reasons for the declining talent of teachers are not hard to find. There haven't been jobs available because the downswing in the population cycle has meant a period of falling school enrollments. Teachers' salaries have declined relative to other professions during the past decade. The feminist movement is clearly a factor. The talent of men entering the teaching profession has remained approximately constant over the last ten years, whereas there has been a sharp drop in the talent of women. Many of the bright, highly-motivated women who used to enter teaching are now getting MBAs, law degrees, engineering degrees, medical degrees--and why shouldn't they? But the fact poses a problem for education.

A second major problem is the quality of school reading materials. By school reading materials I mean (1) basal readers--the graded anthologies especially prepared for use in teaching reading (2) textbooks in social studies and science, (3) teacher's manuals, and (4) workbooks and exercise sheets.

The Center for the Study of Reading has made a major investment in the analysis of school reading materials, so I have available volumes of data and examples (see Anderson, Osborn, & Tierney, 1983). However, time permits only a brief summary.

With respect to basal readers, they are different in important ways from material for children that can be found in a library or a book store. For instance, they less often reveal directly the feelings, goals and motives of characters (Bruce, 1983). Probably this makes basal reader stories both less interesting and harder to understand.

It is easy to be a sensationalist if one chooses examples from the very earliest selections in basal readers. These selections frequently do not tell a story. They do not tell a story because they have been graded according to something called a "readability formula." For those among you who are uninitiated, a readability formula says, "Use easy words. Use short sentences." In the first grade, this means extremely easy words and extremely short sentences.

The readability formula has a baleful influence on school reading materials. Early basal reader selections are full of words such as "he", "it", and "one." The problem is that it is frequently impossible to determine the referents of these terms. Thus, the text has been made more readable in only a superficial sense. It has been made less readable by any reasonable definition.

At all grade levels, short sentences are frequently achieved at the expense of coherence (Davison, 1983). Connecting words such as "after", and "but" are removed. The consequence is that the children are left to figure out on their own how the propositions are supposed to be related to one another.

My colleagues and I believe that textbooks in social studies and science are distressingly poor. Many consist of little more than vaguely related lists of facts. Abrupt, unmotivated transitions are frequent. Textbooks are as likely to emphasize a trivial detail or a colorful anecdote as a fundamental principle.

For instance, in a section of a text about the building of the transcontinental railroad, one quarter of the words and the most salient paragraph in the text was about someone named Leland Stanford who in Promontory, Utah on May 10, 1869 swung a sledge hammer at a golden spike and missed. A close analysis of the sections from several textbooks on the building of the transcontinental railroad revealed that none of them explained clearly why people in this country wanted to build the railroad, what the plans were for accomplishing the task, how it was actually done, or what happened as a consequence (Armbruster, 1982).

According to publishing executives, there is an insatiable demand for workbooks and exercise sheets among school teachers. This is regrettable since a thoughtful analysis by Osborn (1983) suggests that such "seatwork" is seldom instructive for children who do not understand some skill. On the other hand, for children who do understand it, the sheet is probably busy work. The directions for workbook pages and exercise sheets are frequently confusing for the hard-to-teach child. Responding to pages and sheets involves circling letters, drawing lines, or writing words in blanks. It almost never involves writing as much as a whole sentence.

As a rule there is little correlation between seatwork exercises and the basal reader selections and lesson guidelines in the teacher's manual. One reason for this is that it is current practice in the publishing industry for independent teams of people to prepare these components. Often seatwork exercises are subcontracted to other publishing companies.

A thorough study of teachers' manuals indicates that most contain a smorgasbord of suggestions that encourage teachers to flit from topic to topic and activity to activity (Durkin, 1983). This is part of the explanation for the fact that the typical reading lesson is disjointed (Mason, 1983). Manuals are painfully explicit where reasonable people would be able to figure out what to do on their own, but they become vague and sketchy where what a teacher ought to do to bring life to a worthwhile lesson might be difficult to conceive. There are surprisingly few suggestions for direct instruction in teacher's manuals. Most space is given to suggesting questions to be asked and to recommendations for practice and review.

Systematic observation indicates that there is very little actual instruction in reading in most classrooms. Durkin (1978-79) completed three studies involving a total of 17,977 minutes of observation during reading and social studies periods in a number of third through sixth grade classrooms in several Illinois schools. Of this total, she found only 82 minutes that she was willing to count as direct, teacher-led instruction in study skills or in reading comprehension beyond the level of individual words. This amounts to a little less than one-half of one percent of the time. A strict definition of instruction was used in these studies, according to which, for instance, all questioning was classified as assessment, not instruction. Still, these and other studies around North America (e.g., Neilson & Rennie, 1981) show little instruction by anyone's definition.

What does happen during reading period? In the typical classroom in the first three or four grades, the children are divided into several groups according to ability. While one group works with the teacher, the others complete skill sheets at their seats. The children in the reading group are introduced to the new words in the day's basal reader story. Then the story is read. It may be read silently, but more often the children take turns reading it aloud with corrections of mistakes by the teacher as needed. Next the story is discussed and the teacher may provide instruction in some aspect of reading. Finally, directions for seatwork are given.

Taking turns reading the day's story aloud is an activity that consumes a lot of reading period time. This practice is generally deplored by reading educators. Even casual classroom observation will reveal that it is boring and inefficient. A good, recent study completed by Leinhartdt, Zigmond, and Cooley (1981) showed a negligible relationship between the amount of class time children spend in oral reading and gains in reading proficiency.

By far the greatest amount of time during the reading period in most classrooms is devoted to workbooks and exercise sheets. Estimates range from 35% to as high as 70% (L. Anderson, 1983; Mason, 1983). Leinhardt, Zigmond,

...nd a nonsignificant relatio[illegible]ip--trending negative--between ...[illegible] time spent on seatwork and gains in reading.

In the Leinhardt, Zigmond, and Cooley study, the classroom activities that had significant positive associations with improvement in reading were amount of silent reading and amount of direct, teacher-led instruction. The problem is that there is very little time devoted to silent reading in most classrooms and, to repeat, there is even less direct reading instruction. Leinhardt, Zigmond, and Cooley (pp. 357-358) "observed students engaging in many nonreading activities throughout the day, even during times that were set aside for reading. For example we found close to one hour of each student's day was spent on management chores or waiting... Teachers used an average of only one minute per day... to explain or model correct elements of reading. Teachers must organize their time so that these activities are increased."

A fourth and final problem is inadequate teacher education, supervision and staff development. Teacher education in this country, perhaps never what it should be, is now in disarray (see Sykes, 1982, for an analysis). With respect to supervision and staff development, school effectiveness research indicates that schools in which there is strong instructional leadership and in-classroom help for teachers produce gains beyond the expected on a variety of indices (see Samuels, 1981, for a summary of this research as it related to reading). Regrettably, there is not a tradition in this country of principals being instructional leaders. While there is state and local variation, too often the elementary school principal is a former high school teacher who has never taught a child to read, and never tried to cope with a child who cannot read.

Another candidate for the role of instructional leader is the reading "specialist," usually a person who was a good classroom teacher who has received extra training in reading. Unfortunately, reading specialists are deployed as remedial teachers who pull children out of regular classes to provide one-on-one instruction. This interrupts the regular teacher's lesson. Indeed, I have heard reports upon more than one occasion of children being taken out of class during the reading period in order to receive reading instruction! Pull-out remedial programs are costly and inefficient. Common sense suggests that they lead to divided and diminished responsibility; no one is fully accountable when children fail to learn to read.

I have painted a bleak picture of reading instruction in the United States today, but I submit that within the limits of available data it is an accurate picture.

Computers and Reading

Can computer technology help solve the problems in reading instruction? Well, there is no doubt that it could help. I am not sanguine about much help within the foreseeable future, however, because despite our best intentions, it is my expectation that the principal use of computers in reading over the next decade is going to be to automate practices of dubious educational value. Most of the programs I see sweeping onto the marketplace could be called automated workbooks dressed up as games.

There is no a priori reason to suppose that the pedagogical acumen of people who write computer software is going to be any greater than that of people who write paper-and-pencil workbooks. In fact, probably the same companies who now subcontract to do seatwork exercises for Ginn or Houghton Mifflin will be selling their material to Apple and Texas Instruments in the future. Thus, my dismal forecast is that educational researchers in the 1990s will find that whereas children spend much of their school day at a computer terminal there is slight relationship between time engaged with the computer and progress in reading.

If computer technology is to make a positive contribution to reading instruction, a large research and development effort will be required. I will mention three projects that may be worth the investment.

One that would demand a long lead time and nontrivial advances beyond the current state of the art is the development of intelligent tutoring systems. Such systems require a model of the expert's knowledge of texts in a certain domain, a model of the learner's current state of knowledge, and teaching strategies. Collins and Stevens' (1983) analysis of Socratic teaching might serve as the basis for the development of one kind of intelligent tutoring system. Whether or not such systems proved economically viable for use with school children, they would be valuable as models of exemplary instruction for human teachers.

Another difficult, but probably achievable goal is computer aided diagnosis of reading difficulties. Reading is only a partially observable, partially decomposable process. It is best conceived as a system of interacting component processes (see Rumelhart & McClelland, 1981). This means that root difficulties cannot be counted upon to wear their symptoms on their sleeves, and this is one reason that much that passes for diagnosis in reading verges on the occult. The achievement of Brown and Burton (1978) in modeling "bugs" in children's procedures for doing arithmetic illustrates what may be possible.

An application that is possible now is using computer technology to extend learning environments. Several groups are developing child-oriented word processors and computer networks that link children so that they can correspond with one another and work jointly on projects such as school newspapers. The computer serves as an aid that allows the child to keep mechanics like spelling under control and make them subservient to larger and ultimately more important goals of communication.

Finally, I would be remiss if I did not underline the point that the computer is, at most, a small part of the solution to improving literacy in this country. For large and lasting improvements in standards of literacy, salaries and working conditions must be improved so that a continuing supply of talented people will choose to become teachers, remain in the profession, and advance to positions of leadership. The most pressing material need of the schools is better books.

Indeed, it gives one an odd feeling to contemplate the enormity of the investment in research, equipment, software, and maintenance that would be required for large-scale introduction of computer technology into the schools when everywhere around the nation there are districts unable, or unwilling, even to finance an adequate supply of paper and pencils.

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THE PLACE OF COMPUTERS IN THE TEACHING OF WRITING

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I am told that one of my qualifications for this assignment--to review current writing research for a conference designed to create a research agenda for studying the educational uses of computers--is that I am thought to be neutral on the question of whether computers should be used in the teaching of writing. I am willing to say that I am neutral if you are willing to accept neutral as a synonym for naive. Naive though I am, I have recently been reading reports of new developments in computer-assisted writing instruction--as has any writing teacher who keeps up with the pedagogical journals or who, for that matter, simply keeps an eye on the education columns in the Sunday newspapers. Reading these accounts has made me want to learn more about such projects, of course. But reading them has also, I admit, got me wondering how English teachers are likely to react to the news that computers can help them teach writing. To investigate, I conducted a most unsystematic study: I checked my own reactions, and I asked a few of my friends for theirs. As limited as my investigation was, it still turned up several different reactions; let me cast my findings in the form of predictions. Some English teachers, I predict, will be delighted by the prospect of having computers help them teach their students to write. No doubt such teachers will be especially eager to engage the assistance of a computer in the chores of proofreading students' papers and helping students repair their errors. Many teachers will also be impressed by reports suggesting that computer programs can be devised which will provide coaching and tutoring to students all the way through the composing process. And in either case, the English teacher who looks forward to a new era of computerized writing instruction is likely to be a teacher who wants computers to assume some of the more routine and tedious chores of composition teaching so that he or she is free to concentrate on helping students recognize and solve the intellectual problems that their writing projects present them.

Other English teachers, it seems safe to say, will be far from enthusiastic about the use of computers in the teaching of writing. Some teachers may, at the outset, resist irrationally, caught in the throes of the fear and trembling that Ellen Nold has observed in humanists who encounter computers for the first time. But even after that fear is conquered, a sizable percentage of English teachers will, I suspect, continue to oppose the use of computers in their teaching. Some may resist because they fear for their jobs, especially in places where administrators, or teachers themselves, conceive of writing instruction in medical metaphors: diagnosing problems, prescribing remedies, administering treatments, and assessing the effects of it all. Such teachers may worry that, in time, a well-programmed computer will replace the well-trained teacher in conducting the cycle of diagnosis, prescription, remediation, and assessment. Other English teachers, especially those who do not view their work in these clinical terms, may well resist computer-assisted writing instruction on the grounds that computers are irrelevant to the job at hand and that innovative instructional software is a distraction, or worse, a compromising enticement to members of the video generation. These teachers will argue that in order to learn to write, all a student needs is a pencil, some paper, and a few intelligent and helpful readers.

Such, in any case, were the reactions I found in myself and in my friends. I note them here not, certainly, as the results of research, but simply to make the point that the effectiveness of computer-assisted writing instruction will depend to a considerable degree on whether English teachers understand its possibilities and believe in its value. Not even the most intelligently developed software will have much effect on students' writing development if teachers do not arrange for students to use it regularly and in the contexts for which it is designed. Among the issues, then, that merit attention in deliberations on the uses of computers in the teaching of writing are what English teachers believe about computer-assisted writing instruction and how English teachers interact, or fail to interact, with the machines that are turning up in their classrooms or in their schools' resource centers. I dwell on this point because I think it would be a serious mistake to allow the prospect of computer-assisted writing instruction to revive the fantasy among educational leaders of a teacher-proof curriculum; down that path, I believe, lie boondoggle and dashed hopes of the sort that were strewn in the wake of proposals for instructional television.

While I am at the job of proposing items for a research agenda, let me press a bit further. The reports of experimental programs I have read suggest that the microcomputer revolution offers teachers a new technology for accomplishing the traditional goals of composition teaching. But what exactly are the traditional goals of composition teaching? It is not difficult to assemble a reasonably consistent set of very general objectives from a century's worth of commission reports and curriculum guides, but anyone who has worked in the trade for a while (and anyone who has tried to create a valid and reliable writing test) knows that specifying the goals of writing instruction as they are embodied in classroom practice has long been a vexing undertaking. Yet specifying sensible goals for teaching writing--goals that are at once worthy and realizable--would seem prerequisite to developing computer programs that usefully support writing instruction. Sad to say, my experience as a member of advisory groups that have been asked to specify goals for composition teaching has been that such efforts quickly become either bouts of polemic-swapping or, in cases where the group must produce a consensus, exercises in strenuous abstraction. Part of the trouble, I think, is that such discussions must proceed utterly uninformed by a historical view of the composition teaching enterprise; we simply do not have a thorough and penetratingly critical history of composition teaching in American education. No one, that is, has sorted out for us how much of what composition teachers do, and have traditionally done, is properly understood as aimed at helping students learn to control the process of composition and the conventions of written language, and how much is better understood as giving pedagogical expression to attitudes, values, and goals which, though perphaps defensible in their own terms, have little bearing on helping students learn to write. Thus I propose that an important item on an agenda for research on the uses of computers in the teaching of writing would--and should--be a careful and tough-minded historical study of the goals of composition teaching in American schools and colleges. At the very least, it would seem that before we embark on costly research projects designed to develop computer programs that will do more efficiently what English teachers have been trying to do for a hundred years or so, it would be prudent to figure out why the English teacher's various constituents--employers, parents, teachers of other subjects, English teachers at higher levels, students themselves--have been complaining variously about the English teacher's inadequacies, excesses, and evident failures for nearly as long as English teachers have been in the business of teaching composition.

Having said this much about research we do not have, let me turn now to my assigned task of surveying the research at hand. Research activity on the learning and teaching of writing has inceased enormously in the last six or seven years, stimulated principally by widespread public concern about a decline of writing ability among American students and indeed among Americans in general. Much might be said about the character and significance of this public sense of an American "writing crisis"--we might ask, for instance, how public worrying about students diminished writing skill fits, on the one hand, with predictions of an "information revolution" brought on by advances in computer technology, and how it fits, on the other hand, with the current sentiment that schools must get "back to basics," must restore the discipline of some earlier Golden Age in American education. But here I must set aside considerations of the recent publicity about a writing crisis, except to observe that because much recent writing research has been undertaken as a response to a perceived social problem, some researchers (and some interpreters of research) have been tempted to make grand claims about achieving a revolution in writing instruction, claims that rest on evidence from relatively modest studies. I do not believe that writing research over the past few years has provided the basis for a revolution in writing instruction, but I do find that recent research does yield a number of insights and does raise some challenging questions. I should also note, as I clear the ground for my review of this work, that recent writing research has been kaleidoscopically interdisciplinary; studies have been undertaken by cognitive psychologists, by linguists, by anthropologists, by specialists in rhetoric and literary criticism--and by educational researchers who have adapted to their purposes various goals and methods from one, two, or even three of the research traditions I have just listed. And yet, perhaps because the field has so recently expanded into an educational research specialty of its own, there are very few lines of inquiry which have attracted several different research groups whose studies build systematically on solid conclusions from work done in earlier investigation.

Because the recent work is various and in some respects scattered, any scheme for organizing a brief review is necessarily somewhat arbitrary. My method here is to formulate four large questions which seem to me to contain most of the recent research. (I recognize that some readers may find alternative schemes more appealing. The curious reader who wishes to develop his own overview may wish to start, as I did, by considering the reports and essays in recent volumes edited by Cooper and Odell [1977, 1978], Gregg and Steinberg [1980], Whiteman [1981], Frederiksen and Dominic [1981], and Nystrand [1982]. Taken together, these collections make a good starting point for anyone interested in surveying current writing theory and research. The questions I have fashioned to organize my discussion are: 1) What is the status of writing in American society? 2) What are the characteristics of effective written texts? 3) What are the components of the composing process? 4) How do children learn to write? My plan is to take up each of these questions in turn, and then to conclude with some general comments about how people learn to write and how computers might be able to help.

What is the Status of Writing in America?

My phrasing in this question is borrowed from the title of Edward P. J. Corbett's essay, "The Status of Writing in our Society" (Whiteman, 1981), which Corbett first prepared as a presentation to the National Institute of Education Conference on Writing in 1977. Corbett begins his discussion by asking whether writing will "continue to play a significant role in the political, professional, cultural, and business affairs of our society during the last quarter of this century." The question is an important one, Corbett suggests, because the answer will control what English teachers will be teaching in the years ahead. Corbett concludes, more on the basis of rumination than extensive investigation, that Americans will indeed continue to write, and he suggests that the kind of training Americans will need, and for that matter need now, is in practical types of writing ("When students are exercised solely in writing literary essays, to the exclusion of more utilitarian kinds of writing, they are being scandalously short-changed" [p.49]). The English teacher who sees this much will also see, Corbett notes, that "students will have to be exercised primarily, if not exclusively, in Edited American English. That is the power dialect in our society. That is the dialect that provides students with an entree into the mainstream of society" (p. 52).

These are familiar observations--that English teachers too often emphasize the special discourse of literary analysis when their students in fact do not want or need training in literary criticism, and that English teachers who allow students to write in spoken forms are failing to prepare students for life in the mainstream of American society. But the large issue Corbett addresses, the future of writing in America, has only quite recently begun to draw the attention of composition teachers and researchers. The empirical side of this interest has taken the form of studies of writing in the "real world" (as distinguished from writing in school). A number of investigators have undertaken surveys, often sending questionnaires to alumni of the institutions in which the investigator works. (See, as an example, Robert R. Bataille's article, "Writing in the World of Work: What our Graduates Report," which appears in the October, 1982 issue of College Composition and Communication.) A few researchers have conducted thorough observational studies--a notable example is the work done by Lee Odell and Dixie Goswami (see their article, "Writing in a Non-Academic Setting," in the October, 1982 issue of Research in the Teaching of English). Yet more ambitious studies have been proposed by John Szwed (see his essay, "The Ethnography of Literacy," in Whiteman, 1981).

Research on the status of writing in American society has an important place, I think, in the larger field of American studies, and it would seem especially productive if ethnographic studies of the kind Szwed proposes were placed in the intellectual context of recent work by social historians on the history of literacy in America. I have the impression, however, that when composition researchers study writing in the real world, and particularly in the work place, the hope--among those who grant money for such projects, if not among the researchers themselves--is that such research will have very practical value for composition teachers. When studies reveal brisk writing activity in the world of work, they can be used to support the argument that composition teaching should have a significant place in school and college curricula. Writing is pervasive in America today, such arguments usually run, especially in the professions and in managerial jobs; the rise of electronic media has not rendered writing obsolete. People, especially successful people, still write, and schools must continue to prepare students for the writing tasks they will face out in the working world. Studies of writing in non-academic settings can also be used, of course, to support the argument that school and perhaps college composition programs should emphasize practical skills and offer practice in using non-academic forms of discourse. This argument rests on the assumption that writing instruction should be utilitarian, indeed in a general sense vocational; it is an argument that can be heard these days in most realms of composition teaching, but most frequently, I find, in professional discussion of teaching writing to the academically disaffected or unsophisticated (for a particularly interesting example, see Heath, 1981).

The uses in institutional politics, of research on the status of writing in American society are, I suppose, obvious enough, but I am not sure of its value to the teacher in his teaching. We who teach writing should, of course, be interested in the writing that people do outside of school; in fact, we probably ought to be doing some of it ourselves from time to time. And when we teach specialized writing courses that are supposed to train students for a specific job, or even a particular kind of job, our understanding of the pertinent vocational forms and uses of writing ought to inform our teaching very closely. Even when we are teaching more general courses, we are wise to inform our teaching with facts and observations about writing in many situations, and not to limit our ideas about writing, or our students' ideas about writing, to the sorts of discourse familiar in schools and colleges. But we should, I think, resist too complete a utilitarian conception of the goals of writing instruction. We ought to keep in mind, and inform our teaching with, the conception of writing instruction that holds that the development of writing ability involves, at least in part, the development of the use of language as an instrument of thought--the use of language to raise difficult questions, to formulate careful answers, to read and revise one's own formulations. This way of using language is not limited to academic discourse, and it is an activity available, in the right circumstances, to children as well as to adolescents and adults; it can result as easily in narratives of personal experience and thoughtful practical communication as in such specialized forms as the critical essay.

And certainly the case can be made that a student who has practice in using language as an instrument of thought (the phrase is from Bruner, 1977) has developed analytic skill that may be useful to him in some jobs; but even in making that case (which is one aspect of the familiar argument for the liberal arts in American education), we must be ready to concede that the student who is exploring the use of language as an instrument of thought is not necessarily learning a vocational skill.

Much more might be said on this point, but it seems most appropriate here simply to underscore my earlier point that if we are to recommend research on how computers can help teach writing, we had better be prepared to think hard about the goals--and hence the justifications--of school and college composition programs. Recent studies of the status of writing in American society, and the ways in which the results of such studies are used both to support the existence of composition courses and to shape their contents, will press the issues of goals and justifications upon us, whether we like it or not.

What are the Characteristics of Effective Written Texts?

Writing teachers need good descriptions of effective writing, both to define the target we are teaching to and to establish criteria for evaluating our students' written work. Traditionally, our notions about what makes prose effective have come from three sources: 1) models of readability, on the plausible assumption that the features that make texts readable are the features that students ought to strive for in their writing; 2) what we, or our textbooks, understand as the characteristics of especially admirable pieces of writing (the essays of E. B. White, say, or George Orwell, or, more recently, Joan Didion and Lewis Thomas); and 3) what the folklore of our profession, as it is transmitted in textbooks or in the faculty lounge, tells us are useful devices for imposing order on students' essays--one-paragraph introductions, three-paragraph bodies, and one-paragraph conclusions, a topic sentence at the head of every paragraph, and the like. When we are judging the writing that students produce not in our courses but in more formal testing circumstances, our criteria tend to be light on discourse features (we settle for a general orderliness, gauged holistically) and heavy on usage and style (we prefer usage that is formal but not frozen, to use Joos's terms, varied sentence structure with occasional periodic sentences, and diction that is definite, specific, and concrete). Whether judging classroom compositions or examination essays, we also, of course, want students to observe conventional grammatical principles, to punctuate properly, and to avoid misspellings, and we evaluate their writing on the basis of their success in managing these mechanics.

What has recent research to say about all of this? For one thing, some composition teachers and a number of researchers have been influenced by the new emphasis in reading research on discourse structures larger than the sentence. We have always been interested in having students produce coherent texts, but lately we have become more interested in specifying the elements that contribute to coherence. Influenced by recent research in cognitive psychology, some writing researchers have begun to look for evidence in writers' texts of their cognitive schemata--their frames, their scripts, their plans. Some composition teachers have told me that they see little more than attenuated rhetorical analysis in recent theories of the influences of cognitive structure on textual form. Whatever the merits of their complaint, I think it is fair to say that writing researchers and teachers alike have been slow to consider the implications of recent reading comprehension research for helping students become adept readers of their own writing-in-progress.

Some composition researchers have also been greatly influenced by Halliday and Hasan's Cohesion in English, which was published in 1976. The attraction of this book is that it offers a theory of linguistically specifiable features--cohesive ties--that, taken together, make an extended text cohesive and give it texture. Working on the assumption that "incoherent" student writing is insufficiently cohesive, a number of investigators have sought to apply the theoretical scheme from Cohesion in English to the job of evaluating samples of students' writing. No doubt interesting results will emerge from some of these studies; the sticking point, though, in much of the work of this kind is that it is very difficult to establish what Roger Brown calls "obligatory contexts" for specific cohesive ties. It is difficult, that is, to establish a fixed "mature" or "expert" model against which a student's use of, say, nominal ellipsis or lexical collocation may be evaluated. There are, it turns out, many options writers exercise in establishing continuity and texture in their writing.

In addition to supplementing our traditional interest in usage and style with new, or newly formulated, insights into text structure and textual continuity, recent research has also pulled us up short at the question of how composition teachers do in fact judge students' writing. Studies by Rosemary Hake and Joseph Williams (1981) suggest that although we composition teachers say we prefer a lean, verb-based style in our students' writing, in fact we award higher marks to students whose essays are cast in a formal, ponderous, nominal style. Either we are careless (a term we use often to describe our students) or we are stuck in a sociolinguistic dilemma; I do not know which. I do know, though, that we could use more sociolinguistic inquiry to help us frame, or situate, the general question of which features characterize effective writing. We need, that is, to bring closer to the center of our attention what seems to me the obvious point that to speak of the effectiveness of a piece of writing is to speak of its effect in a particular set of circumstances, and we need to overcome our tendency to allow vague labels of purpose ("persuasive," "expressive") to substitute for useful descriptions of the circumstances in which people write. I hope that recent work on the contrasting features of spoken and written language in modern literate societies by such sociolinguists as Michael Stubbs and Deborah Tannen, and recent wide-ranging studies of oral and literate cultural modes of thought and expression by such scholars as Jack Goody, David Olson, Walter Ong, Michael Cole, Sylvia Scribner, and Shirley Brice Heath will lead composition researchers to work on the question of how specific contexts influence particular textual features in students' writing. Once we are better able to situate the question of which characteristics make a written text effective, we are likely to produce answers that are more useful than those we have not for evaluating students' written work.

In the meantime, we are becoming more insightful in our understanding of the features of ineffective writing. Mina Shaughnessy led the way with her analyses of the unconventional writing produced by inexperienced writers at CCNY; Linda Flower has contributed the useful concept of "writer-based prose"; Aruthur Applebee has begun to characterize the textual weaknesses in inexperienced high school students' writing. Joseph Williams, on the other hand, has analyzed the features of what he has called "bad mature writing," and has offered counsel for those who wish to avoid such features in his book, Style: Ten Lessons in Clarity and Grace. Recent analyses of clumsy bureaucratic writing and proposals for antidotes are also offered in the Document Design Project's Writing in the Professions and Richard Lanham's textbooks, Revising Prose and Revising Business Prose.

The upshot is that we are becoming more precise about the features we hope to see in our students' writing, and thus we are becoming increasingly able to program computers--those tireless and relentlessly patient proofreaders--to search out features in our students' writing that do not make our list of characteristics of effective texts. The value of enlisting a computer as a proofreader both persistent and patient, even generous of spirit, should not be underestimated. In my experience, composition teachers are often either generous of spirit or persistent, but rarely both. I assume that any computer, on the other hand, can, in time, be programmed to respond to students' writing with both a steady understanding of at least some of William Strunk and E. B. White's rules from The Elements of Style and an unflagging appreciation of E. B. White's lament: "The English language is always sticking out a foot to trip a man. . . . English usage is sometimes more than mere taste, judgment, and education--sometimes it's sheer luck, like getting across the street." Indefatigable and patient though computers may be, however, I do not imagine that any machine will help composition teachers figure out how to cope with the simple truth contained in Robert Frost's remark, "You can be a little ungrammatical if you come from the right part of the country."

What Are the Components of the Composing Process?

The process of writing--what writers do and how they think--has attracted a great deal of interest in recent years from researchers and teachers alike. Some even regard this new interest in composing (as distinct from an interest in the qualities and effects of written texts) as evidence of a Kuhnian paradigm shift. That claim seems to me open to dispute, but there can be no doubt that recent studies of composing have drawn attention to important questions about how people write and how people learn to write that have not received much attention in the hundred years or so that English composition has been a staple of school and college curricula. There are several researchers participating in this meeting (John R. Hayes and Marlene Scardamalia, to name two) whose understanding of the new composing process research is more current and more sophisticated than mine, and so, assuming that they can ably brief us on its particulars, I will limit myself here to some comments aimed at placing the recent work in historical context and some notes on questions about composing that we continue to neglect.

It was Porter Perrin, I believe, who brought the idea of the process of writing into the modern composition textbook tradition. In his first edition of his Writer's Guide and Index to English, published in 1942, Perrin included an entire chapter on "The Writing Process," a subject which, he notes in his preface, he regarded as "basic for the work of composition." Perrin makes clear in his opening sentences of the chapter why he considered instruction in the writing process crucial: "Writing is either hard or easy, as a person makes it. For most people who have not written very much, the chief difficulty is uncertainty as to what they should do. Worry takes more out of them than work." After explaining his assumptions about the causes of inexperienced writers' difficulties, Perrin lists nine stages in the process of writing an academic paper and then takes up each stage in turn, noting the contribution of each stage to the finished work and elaborating with tips for the novice. In the 1950s and 1960s, perhaps in part as a result of the success of Perrin's textbook and surely in part also as a consequence of the rise of several New Rhetorics, many composition textbook authors followed Perrin's lead and incorporated in their books a chapter that instructed students in the steps or stages of writing papers.

It is interesting to note that Perrin himself was evidently firmly committed to what nowadays is often called a "process approach" to teaching writing. In an essay entitled, "Freshman Composition and the Tradition of Rhetoric," published in 1960, he sought to persuade composition teachers to reduce their emphasis on teaching grammar and to increase their attention to rhetoric, by which he meant "the study of the making, the qualities, and the effects of verbal discourse" (p. 124). He especially wanted attention given to the "making"; "The basic premise of rhetoric," he argues, "is that discourse is an act (something done) studied as an art in the old sense. It is the result of a process that can be seen in stages for each of which pertinent advice can be given" (p. 124). He also makes a point of noting that the particular process a writer follows in a given instance is influenced by the circumstances in which the writing is undertaken. "A second premise of rhetoric," Perrin writes, "is that discourse occurs in a situation that defines to a considerable extent the mental 'set' of the writer as well as the content, arrangement, and tone of what is written" (p. 124).

Of course the textbook writers who put the writing process into a tidy sequence of steps were engaged in a pedagogical act, not an attempt at empirical description. It was Janet Emig's study, The Composing Processes of Twelfth Graders, published in 1971, that launched the recent wave of empirical work on how people compose. Among the researchers who have developed this line of research are Donald Graves, Donald Murray, Sondra Perl, Nancy Sommers, James Britton and his colleagues, and Anne Matsuhashi. The studies of composing undertaken by these and others in the field of English education have tended to concentrate on the behavior of writers, with the researcher drawing inferences about a writer's intellectual processes from the behavior observed. More often than not in such studies, the inferences drawn from observed behavior are eventually modified or amplified on the basis of the researcher's interviews with the writers who who have been under observation. Other researchers--notably John R. Hayes and Linda Flower, and Carl Bereiter, Marlene Scardamalia, and their colleagues--have brought the goals and methods of cognitive psychology to bear on studies of composing, and have thus concentrated directly on the writer's intellectual processes. Still, it should be noted that, as some cognitive psychologists readily concede, even the researcher who concentrates directly on the writer's intellectual processes must find ways to do it with mirrors--cognitive operations are interior phenomena, and are not easily, perhaps not ever fully, made available for inspection.

What have been the effects of recent research on composing? In the first place, such studies have been useful in supporting, and in some cases further articulating, the belief among many composition teachers that good composition teaching emphasizes the process and not merely the product of written composition. Although some theorists argue strongly against it, the notion of writing as a sequence of operations is still influential, and, certainly in some teaching contexts at least, that view is quite useful. Sometimes the notion is cast as a series of specific steps, but more often is formulated as three broad stages--"prewriting, writing, and revising," or "conception, incubation, and production." Yet while many composition teachers continue to think about the composing process as a series of stages, cognitive theories of composing are beginning to get wider circulation and are challenging the image of writing as a step-by-step procedure with a picture of the writing process as a network of problem solving tasks, tasks that interact in a hierarchical system rather than lining up in a simple linear sequence. I suppose that some of the fine points of such cognitive theories elude many of the composition teachers who study them; but I also suppose that anyone who has been reading the pedagogical journals or who has spent a summer in a local branch of the National Writing Project is likely to have developed the impression that composition experts have reached a consensus: writers solve problems; revision is recursive.

Recent research on composing, whether from the perspective of cognitive psychology or in the tradition of English education, has given us not only a more detailed and more complex sense of the components of composing, but also some intriguing and potentially very useful hypotheses about the differences in composing behavior and cognition between expert writers on the one hand and novice writers on the other. It seems likely that program developers will work at using these hypotheses to create computer-based tutoring programs in composing, programs that predict the shortcomings of an inexperienced writer's composing strategy and that instruct him in how to adjust his strategy to make it match more closely a generalized model of how experts compose. Basic research on composing and technical refinements in computing are needed, however, before the potential of this use of computers in teaching writing can be fully evaluated.

For all the insights produced by recent studies, it must be noted that as a general line of inquiry, composing process research still has a way to go. We have had, to cite one important limitation of the work to date, virtually no research that seriously attempts to unite the two premises of rhetoric that Perin noted more than twenty years ago--first, that writing is an activity, a process, and second, that character of the activity of writing in a particular instance is significantly shaped by the situation that gives rise to the act. At the moment, the first premise serves as the guiding assumption of the writing research undertaken by most cognitive psychologists, and the second premise is the central assumption of writing research conducted by educationa. anthropologists. Too often, these two camps of researchers regard each other with great suspicion. The result is that we generally get abstracted models of the composing process from one camp and detailed analyses of the contexts of specific writing activities from the other camp, with few attempts to discover the relationship between these two kinds of knowledge.

Perhaps the most important reason to build some idealogical bridges between these two camps is to enlist the help of both sides in formulating productive methods for studying the act of sustained writing, writing that is not composed in one sitting but rather is composed over days, months, and even years. We know very little indeed about how people produce writing that is longer and more complex, or which demands more sustained thought, than writing that can be disposed of in one or two classroom periods. We have plenty of material from literary studies and interviews with professional writers to enrich our understanding of sustained composing, but so far as I know we have no data of the orderly sort usually gathered in social science research to help with the job. Vera John-Steiner, I am told, is now at work on a study of how people complete long-term intellectual work, including extended writing projects--her working title is said to be Notebooks of the Mind--and we can look forward to the results of that project; also, we can observe that, for future studies, new word processing technology would seem to greatly facilitate the gathering of data.

In the meantime, though, we must recognize that the knowledge we have accumulated and continue to accumulate is knowledge about the process of composing relatively short and uncomplicated pieces of writing. Such knowledge has its value, to be sure, in part because composition teachers are often expected to teach their students how to write short and uncomplicated reports and essays. It seems a shame, though, to limit the domain of our inquiry, and perhaps thereby to limit the ultimate value of our research, chiefly because we lack the imagination or the academic diplomacy required to develop methods for studying how people produce complex and sustained pieces of writing.

How Do Children Learn to Write?

Elsewhere (Gundlach, 1981, 1982) I have reviewed at some length the recent research on young children and their writing; here I will comment on this work very briefly, noting ust one theme that I believe has some bearing on the teaching of writing to students of any age. In making these remarks, I have in mind particularly studies by Bissex, Graves, Sowers, Calkins, Read, Harste, King, Ferreiro, Clay, Sulzby and a number of others whose work has been strongly influenced by the methods and spirit of recent research in children's language acquisition. Partly as a result of that influence, I think, the results of these studies point to the conclusions that all children <u>can</u> learn to write and that young children are able, given support and guidance from teachers and perhaps parents, to adapt the powerful language learning strategies they employ in learning to speak to the process of learning to write. The more sophisticated arguments advanced in support of these claims, it should be noted, usually depend in some measure on a Vygotskian theory of the child's development of the functions of language. I mention this, alas in passing, because interactive social theories of children's language development no doubt have implications for the construction of interactive computer programs that might help children develop as writers.

The central lesson of recent studies of children's writing development is that the process of learning to write involves more than being taught, or at least more than being instructed in a formal and deliberate way. Children apparently draw on a number of resources as they begin to learn the uses, forms, and processes of writing, and some children, perhaps many, conduct their own experiments with writing well before they encounter formal instruction in either writing or reading. In my view, any composition teacher or curriculum builder stands to profit from speculating a bit about the resources children bring to the process of learning to write: children have, of course, their knowledge and experience as speakers, which can provide them both a knowledge of linguistic form and a "sense of situation" that will serve them well, though not comprehensively, when they begin to write; they have the sense they have made of their observations of people writing and their encounters with written language; they have their reading experience, including their experience of hearing written language read aloud; they have their inclination to experiment with cultural tools and cultural roles; they have their ability to engage adults and other children in helping them solve technical problems; and they have their inclination to cooperate, to accept direction. Such are the resources, I suggest, that virtually all children--and most older students, too--bring to composition instruction. As James Britton has suggested, we who teach composition, if we are alert enough to recognize it, "seek to reap continually a harvest we have not sown." (Britton elsewhere formulates this point about the complex relationship between teaching and learning in less metaphorical and more ominous terms: "We teach and teach," Britton notes, assuming the rhythms of Samuel Beckett, "and they learn and learn: if they didn't, we wouldn't.")

I do not mean to suggest that students will become mature or expert or competent writers without any coaching or instruction; most will not. Rather, I want to make the simple point, obvious yet too often lost from view, that a theory of how people learn to write must be kept distinct from, and must receive our attention prior to, a theory of how people should be instructed in writing.

How People Learn to Write--

And How Computers Can Help: A Coda

Recent writing research has not yet provided enough answers--or even, it can be argued, raised enough of the right questions--to give us a general theory of how people learn to write. I trust that I will be forgiven, then, if here at the end of my discussion I depart from current research and turn to more incidental sources. Consider, for example, a remark made by Elizabeth Hardwick in her recent review of a biography of Katherine Anne Porter (NYTBR, 11/7/82). Hardwick observes that Porter, early in her development as a novelist and short story writer, was "in and out of Greenwich Village, where she met writers and no doubt increased her sophistication about literature and the act of writing." Hardwick joins her clauses with a simple "and," but I think it is fair to infer that she means that Porter became more sophisticated as a writer because she was in touch with, and very likely was reading intently, writers who formed a literary community. This remark caught my attention because I believe that participating in a community of active readers and writers is one way, and perhaps the way, a person develops as a writer. I think this is true not only of novelists and poets, but also of people who learn to write good term papers or effective office memos.

Because I have this notion, my attention also fastened on some comments made by the historian Robert Darnton in his essay, "What Is the History of Books?", which appeared in a recent issue of Daedalus (Summer 1982). In this essay Darnton proposes a general model to account for the life cycle of a book. The model he sketches is of a "communications circuit" in which a book is produced by an author, passed along to a publisher, then to a printer, then to a shipper, then to a bookseller, then to a reader, and then, in a curious sense, back to the author again. Explaining this last connection, explaining, that is, how reader "influences the author both before and after the act of composition," Darnton writes:

> Authors are readers themselves. By reading and associating with other readers and writers, they form notions of genre and style and a general sense of the literary enterprise, whether they are composing Shakespearean sonnets or directions for assembling radio kits. (p. 67)

I am not working my way around to the argument that formal instruction in writing is worthless. I do not hold with Flaubert, who said (if Paul Engle is to be trusted; I have this second hand) that all a teacher can offer a would-be writer is a kiss on the brow and a kick in the pants. Nor do I mean to suggest that students are likely to become writers merely by following the biographical traces of literary figures. What I am suggesting is that if a person participates in a community of active readers and writers, if he reads and writes regularly and if his reading and writing put him in touch with other people, he stands a reasonably good chance of forming notions of genre and style, of developing a general sense of the literary enterprise, and of becoming increasingly sophisticated about the act of writing itself. And I suppose we must conclude, on the evidence of experience if not research, that some people can, by participating in such a community, develop considerable writing skill without much formal writing instruction at all, while others, though they read and write and rub shoulders with fellow writers, stand to profit from all the composition instruction man or machine can provide.

What does this mean for research on the place of computers in the teaching of writing? It means that we ought to ask first how teachers can assemble true communities of active readers and writers, and how teachers can give even the most reluctant students a clear shot at participating in such communities. Then we can ask how computer technology might be useful in these efforts.

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READING

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Questions by any teacher when considering the place of computers in the classroom should range from those relating to theoretical issues to those about practical application. Foremost, computers should focus on teachers, their curriculums, and their students. Research in the effectiveness of computers in the classroom should not exclude looking in depth at children, classrooms, teachers and learning. We should not be so much interested in statistics as in good descriptions of how children are using computers in developing their use of language and how the computer affects children's becoming literate.

Too often evaluation has become confused with research. The research relies on collecting standardized test results, not looking at the reading and writing processes themselves. What is needed is a wider range of reading research methodology and interdisciplinary research within the classroom with real readers and writers using those processes, not standardized test results which do not present enough discourse to really test the reading and writing ability of children.

Reading researchers have become more independent today, although they draw on the work from other fields such as psychology, physiology or linguistics. They develop their own research paradigms and develop their own theory base. Reading researchers and classroom teachers are beginning to work together; perhaps it is also time to add the computer programmer to that team.

If teachers become a part of the computer programming procedures, the materials will not be in conflict with their curriculums. Additionally, the programmer will have an opportunity to learn how the teacher views literacy and learning. By working with the informed teachers, the programmer can use that information to address instructional needs.

Unfortunately, one of the main concerns in the field of reading today is the recognition there are gaps between theory, research and curriculums. Classroom teachers are at odds about what theory on which to base their curriculum or, worse, they haven't developed their own philosophy. Therefore they rely solely on textbook companies to dictate their lesson plans.

Consequently the overall objective of any research should be to build and disseminate reading theory which will truly contribute to the development of literacy in the classroom. By helping teachers understand the reading process, this will enable them to build their individual instructional model, implementing that theory into practice.

At this time materials teachers use to guide and help them improve teaching methods are stating two major theories. For example in a 1977 book, Phonics: Why and How by Patrick Goff, the teacher is told:

> Phonics teaching does, in fact, offer the child significant help in learning to read and spell. The research on the teaching of reading makes this clear. As Eleanor Gibson puts it, the heart of learning to read would seem to be the process of mapping written words and letters to the spoken language; a process of translating or matching one symbol to another.

Teaching reading has been based on the idea that reading consists of a set of identifiable skills and publishers have produced materials aimed at giving practice with these skills.

M. Clark, however, brings out in her book, Young Fluent Readers (1976):

> Teachers have too long been too little aware of the complexity and range of skills that even the beginning reader brings to the reading situation... the teacher concerned with the young child and the beginning reader has had her attention directed mainly if not exclusively, to the lower decoding skills.

Yet, education still feels the effect of Flesch's "Why Johnny Can't Read," Family Circle, November, 1979, which emphasized a phonetic approach. The article pressures and influences teachers to continue such an approach and materials without looking at research on the reading process.

As an undergraduate, in 1967, the only reading theory my course presented was a phonetic approach promoting activities such as presented in the text Personalized Reading Instruction (1961) by Walter B. Barbe:

> At the readiness level it is important for the child to learn how to match letters and match words. By listing in two columns different letters the child should be able to draw a line from the word in the column on the left to the column on the right which is the same. This can be done in a variety of ways but should begin with matching either single letters or words that begin the same. The teacher can then lead into matching words and small letters when the child has learned to match these.

From the other viewpoint Lynn L. Rhodes states in her paper, "Predictable Books: An Instructional Resource for Meaningful Reading and Writing": The Affective Dimension in Reading: A Resource Guide, Indiana University Reading Program-1977:

> Readers have three language systems available for their use. These three systems, the syntactic (grammar) system, the graphophonic (sound/symbol) system, and the semantic (meaning) system, are used in an interrelated manner. The redundancy of the language system and the reader's active predictions about content and language of the story permit an efficient reader to sample the graphic information on the

page. The overemphasis on the graphophonic system prevalent in reading instruction causes the reader to have to use far more visual information than would be necessary if the same graphic information was embedded in whole, natural language.

Kenneth S. Goodman expresses concern about the "Back to Basics" movement. (Commentary, Language Arts, November/December 1978):

> Logically, we should be gearing our schools and preparing our teachers for grand innovations. New curricula, new materials ought to be pouring forth to put the developing knowledge to work. But, in fact, in our very zeal to make literacy universal, in many school systems we are locking out knowledge. The battle is Back to Basics. Truth is to be found by closing our minds to new knowledge, facing to the rear, and glorifying ignorance. This know-nothing movement is institutionalized by state law, board policy, federal guidelines, and even court order. It is set in the concrete of minimal competence, management by objectives, arbitrary skill hierarchies, mandated testing. Schools are ordered to teach all children to read quickly and well, but they are then cut off from new knowledge and the possibility of using it in creative innovations.

Further, two studies that have helped prove that teaching letter sounds is a waste of time were done by Robert Hillerich in Elementary School Journal, "Teaching About Vowels in Second Grade" (Fall 1970) and "First Grade Reading Achievement" (Feb. 1967). Hillerich studied the effectiveness of teaching vowel generalizations to first grade pupils. He compared all first graders (N=742) in two comparable school districts in terms of reading achievement at the end of grade one. In one school district, first graders were taught vowel generalizations as part of the reading program. In the other school district they were not.

Results at the end of the year indicated that those pupils who had not been taught vowel generalizations scored significantly higher in reaching achievement. Most important, the entire difference in reading achievement of the two groups was reflected in the subtest of comprehension, suggesting that excessive attention to the vowels led to overanalysis of words rather than concern for meaning.

In a follow-up study, Hillerich investigated the effectiveness of teaching about vowels in second grade. In this study of six classrooms, two classes of second graders were taught vowel generalizations, two classes were taught about vowels only at the hearing level, to listen for and to recognize the various sounds, and two classes were not taught anything about vowels during the entire second grade year. At the end of the year, the reading achievement test indicated that those who had been taught only at the hearing level scored significantly higher than the next highest group, while the group that had been taught vowel generalizations was lowest in reading achievement. In the conclusion of his findings he stated:

> From the standpoint of analysis of language, vowel generalizations have little validity; from the standpoint of instruction of primary children, they have little effectiveness.
>
> Children have difficulty with vowel rules and are often given extra practice sheets on vowels. Such activities require time for filling in blanks, time which could be devoted to reading or to having fun exploring the language. Most teachers recognize that, once started, children also learn to read by reading.

Teachers have a commitment to teach the way they feel is professional and theoretically sound. The teachers, feeling the responsibility to guide children into literacy, must resolve differences.

How true the statement in the 1978 November/December issue of Language Arts editorial by Julie M. Jenson: "In what field (referring to reading) has so much that violates sense been published, packaged, and inflicted on teachers and children?"

Because of the research I have studied and applied in my own classroom I believe as R. Van Allan expressed in his article, "Personal Language and Beginning Reading," Early Years (November 1978):

> As language matures and positive attitudes about books and reading develop, teachers assume responsibility for helping each child conceptualize, habituate, and internalize a few truths about self and language.
>
> Children, who from the beginning have related speaking, listening, and writing to the reading process, begin to read naturally. It's as natural as learning to converse. Reading for them is not a separate subject in school but a natural part of sending and receiving messages.

My students benefit by participating in a comprehensive language program, because the emphasis is on the development of language processes, basic concepts and the integration of these processes and concepts into a strong language base for effective communication. This approach to instruction in language arts allows for the integration of reading, writing, speaking, and listening in a meaningful context.

The program is comprehension-centered and helps the students focus on gaining meaning while reading. The individual and group activities are designed to develop and broaden concepts and experiences. These activities also generate many natural reading and writing experiences. The oral language which children use and hear daily is utilized as material for instruction rather than fragmented sounds and syllables that are not a meaningful part of their everyday experience. To help the children gain meaning from print, instruction incorporating the three systems of language, graphophonemic, syntactic, and semantic, is used. Isolated use of one system is avoided. The children are encouraged to use the information from the integration of all three systems to gain meaning. The language arts become meaningful because children read, write, listen and talk about activities in which they participate.

This program helps improve existing receptive and expressive skills and develop a desire to read and write to gain meaning for pleasure.

Like listening and speaking, reading and writing are acquired because they are functional and social in nature. As children interact with others in their societies of home, community, or school, they find it necessary to use language in a variety of ways and for a variety of purposes. M.A.K. Halliday has identified seven functions through which a child acquires oral language or, as Halliday puts it, "learns how to mean," Learning How To Mean (Halliday, 1975). These seven functions have provided others a basis for drawing parallel functional motivations for learning to read, and a third parallel follows easily--motivation for writing.

(K. Goodman and Y. Goodman, "Learning to Read is Natural." Presented at the Conference on Theory and Practice of Beginning Reading Instruction, Pittsburgh, April, 1976 and Barbara Burk, "How Children Learn to Mean Through Oral and Print Activities." Presented at the Conference on Reading, University of Missouri-Columbia, October, 1978.)

Functions of Language	Activities
Instrumental "I want"	1. Write captions for pictures and stories. 2. Create situations such as setting up a store. 3. Ask others for things in writing (ordering from an ad, letter to Santa, information from a resource person).
Regulatory "Do as I tell you"	1. Make signs to express safety, health, eating habits. 2. Create in maps, pictures and print directions to homes. 3. Write rules for pet and plant care. 4. Write science experiments. 5. Write recipes.
Interactional "Me and you"	1. Use a classroom post office. 2. Set up work and interest groups with elected officers as a club. 3. Form committees for special projects. 4. Engage in partner reading and writing. 5. Engage in written conversation. 6. Write text through the language

	experience activity.
	7. Share work with other children, groups or classes.
	8. Work together to write and act out plays.
Personal "Here I come"	1. Write books about own interest, letters to penpals, autobiographies, personal survey.
	2. Express feelings through discussions and writing and drawings.
Heuristic "Tell me why"	1. Discuss, read, and write about points of interest in science, math, social studies.
	2. Ask and answer questions through direct experiences (make apple butter, visit petting farm, fire station, etc.).
	3. Read to children daily.
	4. Children read and write daily.
Imaginative "Let's pretend"	1. Story-telling, drama.
	2. Writing of plays.
Informational "Something to tell you"	1. Produce language by describing an object, event or person; make a newspaper, a poster, a report.
	2. Send messages.

Every teacher waits for an incident which makes all her years of training and devoted work seem worthwhile. The moment I cherish came when I was interviewing children about reading. "What would you like to do better as a reader?" I asked. "I'd like to write books for kids," some replied. "I'd like to be a writer," others responded. "Maybe someday I'll be a famous author," answered several more. Why did these replies excite me as a reading teacher? Because these children had underscored the basis of my reading theory--that, in constructing meaning for others through writing, children gain the understanding that reading is a process of getting meaning from print.

From the very beginning of school, I address my first graders as readers and writers. An exciting atmosphere prevails, one in which risk-taking, experimentation, and persistence in reading and writing are accepted and encouraged, with an emphasis on "making sense."

Robyn, using a picture as a stimulus, writes...

My wave's ror i make reflektions i carry boats for i am the river

In writing to a professional author, it is obvious that Matt views himself as an author as well:

Dear Walter

I Like The Book you roet The Drragen taeks a wiEF. I Like KietS and Drragens alot. I Like To Make BookS too. How Log did it take to riet the Book? I will sand you a Book I Maes. Waet is Your aaedrrase? and ziq cowd?

from Matt K.

After deliberately stomping on my bare toe with his combat boot, Bill, the class challenge who would test any teacher's endurance, writes...

Dear Ms Copelan

I am vre sre for stopeg on yor feet and doegg rog tag I am goyg to bee good

From Bill

Not too many years ago I would have viewed these writing pieces quite differently, focusing upon spelling, punctuation, and grammatical errors, and overlooking the power of children as meaning makers. I firmly believe that these children write because the classroom atmosphere encourages taking risk with language and because they know they are respected as individual learners.

In my ninth year as an elementary teacher, I began to question my method of teaching reading, upon hearing of the approach called "whole language." Because I needed and wanted justification and proof of its effectiveness, I began a five-year graduate program in the area of reading, and became actively involved with research in my own classroom to determine what instructional method would most benefit my students.

Like many other teachers, I previously relied on my textbook manuals and standardized tests to guide my instruction, not formulating a personalized theory base of teaching reading. Due to the information, research, and mostly the progress of my students, I formed a strong theory base which reflects the whole language approach.

Whole language teachers foremost respect children striving to learn the reading and writing processes. A whole language classroom is a place in which children can continue their language learning in a positive way, one in which they can take risks, not being afraid to make mistakes while making sense of their world. The whole language teacher is concerned with the effect schooling has on children, realizing that classroom encounters can make the difference between children becoming active learners and passive casualties of the educational system.

Teachers become facilitators of language learning with a major goal being to issue invitations to students to read and write, helping them become responsible owners of their own language. They are encouraged to be risk-takers and independent decision-makers. Invitations are offered with the use of a vast number of materials and activities that give children a real purpose for reading and writing.

The materials and activities offered in a whole language classroom take the place of the all-too-frequent reading groups that waste readers' and writers' time by using artificial reading activities and fragment language by teaching isolated skills, consequently stifling progress and frustrating children.

The whole language approach personalizes that reading program by meeting the specific needs of each student. Children do not learn isolated skills, then read and write, but become proficient readers and writers by reading and writing. When children learn to ride bicycles, we don't have them memorize all the parts before getting on to ride. Instead, they learn by riding, falling, and trying again. They learn through practice and mistakes.

By sampling print, predicting, confirming or rejecting their predictions, children construct meaning--through reading.

By selecting and considering topics, drafting, revising and editing, children construct meaning through writing. Their writing should never be judged on the basis of a rough draft. After all, how many writers stop there? We may have lost many gifted writers because the expectations of teachers concerning quality in writing (form) were out of perspective with the focus of the child (message).

> April:
> Terry, a new boy in class, writes a story:
> A tger A gril

Writing from the perspective of a puppy, Matt J. produces a rough draft, to be revised, and then edited.

After Matt writes his rough draft, he and I hold a conference, in which he finds many of his punctuation, spelling, and grammatical errors. After the revision process, he consults friends and the dictionary to share his final story.

> My brother Russell and I were playing when we were getting ready to be sold. We heard Matt say that he need a puppy. We tried to be real good so that we could be one of the puppys. Then we found out how it was. When we got home he shut us up and wouldn't let us out of the house or feed us, so we got hungry. Finally he let us out but we had to find shraps. One day I told him that a puppy was a big responsibility and that he would have to feed us everyday and a puppy is not just let in and out. He said that he didn't have enough money I said you should have thought about it before you got us. So he got a doctor feed and we got lots of food.

The following classroom activities are some frequently used in the development and implementation of the whole language approach:

a. A Sustained Silent Reading Program - in which the class silently reads self-selected materials for a given period of time daily - is recommended because it is believed that children learn to read by reading as suggested by Frank Smith in Reading Without Nonsense (1979).

b. Yours, Mine, and Ours Selections - This is an individualized method of book choices. The Yours selection is made by the teacher. The Mine is the student's choice made without adult influence. The Ours selection is made by mutual agreement between reader and teacher. The class could be divided into interest groups for discussion of reading material (Goodman and Watson, 1977). A reading program to live with: Focus on Comprehension. Language Arts, Nov./Dec. 1977, 54(7).

c. Personalized Reading - This is a method for providing books that include stories of people who have similar problems or experiences relating to the reader. A good resource is The Bookfinder by Dreyer.

d. Writing - In agreement with early writing researchers, an important aspect of the whole language concept is the student's ability to use writing to get to reading. C. Chomsky "Write First, Read Later," Childhood Education 1971, proposed that by dealing with writing before reading, children will have the opportunity to become active participants in teaching themselves to read.

Donald Graves suggests three stages to encourage writing. ("Balance the Basics: Let Them Write." Learning, April, 1978.) First, there is a precomposing stage which is a preparation time for stimulation through art, reading, discussion, reflection or reaction to experiences. The next stage is composing, when the actual construction of materials occurs. The last, referred to as the post-composing stage, is the time to observe what children do with the product created. They may share it, solicit approval, proofread, edit or ignore it. Graves believes, "Children should rate their own work and be aided in developing their own criteria."

Since it is recommended that children be encouraged to use their writing ability, some of the possible activities are: Sustained Silent Writing, based upon the Sustained Silent Reading concept, a daily journal, written conversations, letters to pen pals, writing text for wordless books, making their own fiction and nonfiction books.

e. Predictable Books - Use of stories with predictable language allows readers to predict what the author is going to say. The more readers can predict the content and the language of a story, the more readable the story becomes to them, making the reading process more accessible to beginning readers. Using predictable materials develops the readers' confidence in their ability to handle print.

f. Extended Literature Activities - Involving children with good children's literature is of prime importance; children need to be read to daily. The stories can also be used to stimulate additional reading and writing activities. For example:

The teacher reads The Little Old Man Who Couldn't Read by Irma S. Black.

This book relates to jobs, economics, reading, writing, art and math. After the book has been read, discussion of the story follows. The children are then encouraged to play a game using food product containers. As the teacher holds up a box a child reads the label becoming the owner of that box. After all the children have an item they are given paper to make an advertising poster of their product. Discussion of how the posters will be used in a grocery store they will set up follows in a brainstorming session to decide how they should set up the store. Such things as the jobs at which people work in grocery stores, how various foods are arranged within the store, and what customers need before going to the store are discussed. The store is then set up. Problem solving activities are centered on making objects for the store, making money, making a cashier stand, making advertisements, where to place products, making shopping lists, actually shopping. A field trip to a real grocery store adds valuable means of bringing the child's real world to the classroom.

Material on making money, grocery store settings, food processing, are made available for the children to read.

Using these types of activities raise a concern about the use of computers in the classroom dealing with reading and writing because language learning is being viewed as a social and natural process and the language arts curriculum is being generated by the needs of students to interact with others to become proficient language users.

To date the computer software I have seen comes directly out of a skills acquisition model of reading. The focus is on small units of language (sound symbol relationships, syllables, morphems, etc.). At best, I've seen rather contrived short stories (one or two paragraphs). In effect, the skills sheet or the textbook format of a story followed by end of chapter test questions has been transferred to the screen.

Because of my reading program I feel it is essential that the use of computers not be a means of providing meaningless time-wasting tasks; rather the use of computers should advance children in their encounter to become proficient readers and writers, supportive of the language arts curricula that respect children's natural language ability and desire to become literate.

TEACHING AND TEACHING WRITING IN THE AMERICAN SCHOOL

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I have been asked to describe and assess the teaching of writing in the American high school today, as well as to reflect on computers in education. That's a big job. If I were teaching in New Zealand, a country which I closely observed the past summer, I could analyze their writing program. It is a national program, mandated and operated by the federal government in the capital of Wellington. But here in the United States we live and work in high schools whose teachers, administrators, and curricula are guided by myriad forces--local, state, national, individual and departmental.

So what is the Truth?

For the moment, I am going to take my direction from those 19th Century Transcendentalists who believed that Higher Truth or Macrocosm can be discovered by examining Microcosm. And so I am going to discuss first Monday, September 27, 1982, at West High School in Iowa City, Iowa--especially in Room 105. That's my school; that's my classroom. Microcosm. And then I will try to relate my experience to what I believe is happening in America. Macrocosm.

Teaching in an American High School: September 27, 1982

(1) 7:30 a.m.

I arrived at West High School with ten paperback copies of works by Ernest Hemingway, which I had purchased at a Des Moines used book fair on Friday night. Our low English department book budget needed some personal assistance, and I was already thinking ahead to my spring seminar on the Nobel Prize winner. Even though that seminar would now be three sections, I knew that this was the perfect setting for teaching both literature and writing: only sixteen students in each section working together in a dynamic process of in-depth study of a single author. Here we would read aloud, discuss Hemingway's style and themes, and explore everything from pre- writing to peer evaluation, from skill goals on such things as introductions and sentence combining to composing and editing seven position papers in twelve weeks.

With less than an hour before my first class, I hurried to the school office for my mail and then to my classroom where I stacked the books and checked my lesson plans for the day. My mail included an approval, without funding, for a one-day professional leave to attend a writing conference at Drake University and a reminder that my faculty committee on writing course descriptions for next year's 9th grade handbook would meet Thursday. The committee of four includes two English teachers.

Just as I prepared to go to the media center for today's audio-visual equipment, Electra Coucouvanis came into the room--smiling. A senior who had been a member of my college prep classes last spring, she had just received notification that she was a national finalist in the writing competition sponsored by the National Council of Teachers of English (NCTE).

(2) 8:20 a.m., Period 1, American Literature

After taking roll, I returned the corrected 30 Line Alternate Basic Skills Test answer sheets to those students who had voluntarily come in after school last Thursday to improve what I believe are the cosmetics of writing--twelve mechanical skills ranging from spelling to parallel structure. Concerned about student maintenance and consciousness of these important mechanical skills, especially in content courses, I had developed a proofreading test program which included review and instruction of the twelve skills, a test with high interest content, a student diagnosis sheet to record individual errors, and a reward system for students willing to take an alternate test after the answers had been discussed. I complimented those students, noting an 80% improvement on their previous scores.

Next I announced that John Leggett, author and director of the University of Iowa Writer's Workshop, had agreed to meet with our combined American literature classes next Monday to discuss writers and writing.

Finally, I reminded the students that Wednesday would be the day for writing and proofreading their latest assignment, an analysis of a short story of their choice. Though we had spent nearly four weeks discussing modern short stories and a method of literary analysis, some students revealed very natural concerns about focus. Some were concerned about the quality of their latest drafts. I encouraged the first group to focus on two key questions: "Does your story relate to you, to your life? Can you relate to the plot or a character or the central idea in concrete terms of something you have read or felt or done?" Then I set up appointments with the others to see me during my conference period or after school today or tomorrow.

Now came the lesson: the American author. Since I wanted my students to know something about people who write and publish, we had spent last Thursday discussing how authors are published and on Friday seen a film on Ernest Hemingway. Now it was time for them to become actively involved through research, speaking, listening, and writing. So, I described their next assignment, pointing to a list of fifty writers' names on the chalkboard. Each student would select an author; find anecdotal, biographical, and literary material about the author; and present a speech which his/her classmates would eventually use in writing a profile essay on what American authors seem to have in common. After the students volunteered for their authors, I began their note-taking by giving a seven minute speech on Thomas Wolfe. In the final minutes of the period, I showed slides of Thomas Wolfe and the Munich Oktoberfest, having already discussed the writer's unfortunate fistfight at the fair in 1937 and his account of the fair in <u>The Web and the Rock</u> (1939).

(3) 9:20 a.m. to 11:20 a.m.

I repeated the American literature lesson to my second and third period sections. Now I had taught a total of 82 students.

(4) Lunch

During our half-hour lunch, I ate with a young English department colleague and a student teacher of English. Kevin, who teaches one of our school's three strictly defined writing courses, was depressed. He had just read a newspaper article about proposals for encouraging mathematics and science teachers to stay in high schools. "They want to pay those teachers more than the rest of us," he said. "This has got to be my last year. I have all but the dissertation, but there is no future in this profession." Kevin is a popular and well-trained English teacher, and I told him that he was what young people desperately need. "By the way," I asked, "how many hours do you have in writing or the teaching of writing?" "At least thirty," he told me. Then I asked the student teacher the same question. "I took required Rhetoric as a freshman," she said, "and a friend and I taught a unit on writing in our English methods course."

(5) 11:55 a.m., Period 4, American Humanities

This interdisciplinary elective of twenty-five juniors and seniors had finished "The Idea of Culture" section and then chosen the 1960's for study. Last week they began reading social history for their small group discussions next week.

Today, I would initiate a second assignment: Activity Committees.

Activity committees would give the students an opportunity to explore the 1960's in a different way--through research, writing, speaking, visualizing. After I explained the choices, they volunteered: some to make a classroom bulletin board to develop a visual concept of the decade, others to collect and present 1960's artifacts, and an even larger group to make a class handbook. While the first two committees would work closely together, the handbook committee would divide into writing teams on such things as "The Story of the Year", slang, fads and fashions, "Man of Decade", and "Woman of the Decade". Finally, I described the available materials in the classroom and the plans for tomorrow's research in the library and for committee meetings.

(6) Conference Period, 5th Period

No classes now. I hurried to the library to remind the head librarian of tomorrow's researchers for both literature and humanities classes--and I took along the A-V equipment for the media center. I knew that I must get back for my conferences on rough drafts. In the halls I met Tukkar Hokanscn, now a senior and another former student. He asked me to look at a rough draft of a paper that would be part of an application for becoming a Presidential Scholar.

(7) My 6th Period is a 1930's section of American humanities, and I prepared them for Activity Committees--only I took volunteers for a radio script which they would tape as their final product.

(8) 3:50 p.m.

The buzzer sounded, ending 6th Period, and I returned to my desk to study Tukkar's manuscript. I saw that he had good ideas and organization, but his focus was too general, too flat. When he arrived, I suggested that he convey his love for Iowa City by doing what he does best. "Take them on a bicycle ride," I suggested. "You are a champion racer, and you have ridden every street in this town." Tukkar smiled, his eyes widening. "That will work. I'll do it!" he said, reaching for his manuscript. Then he headed for the door, saying, "See you tomorrow."

Tomorrow. I began to think of tomorrow's lessons and those 82 short story analyses for Wednesday. Brain-wave, click: about ten minutes a paper, 820 minutes, over 13 hours of correcting and suggesting, mostly at home.

And then I was brought back to reality. "Could you help me?" a troubled voice asked. There was Laurie Schintler, a junior from my 3rd period. And behind her was Phil Chu, another junior. "I think I understand my story," Laurie said, "but I would like to talk with you about it before I begin writing tonight." "Sure," I said. "Let's talk about it."

"Before you begin," said Phil, "is it all right if I turn in my analysis on computer paper? We have a word processor at home."

<u>Teaching Writing In America</u>

The Transcendentalists believe that a drop of water reveals the river. But can an English and humanities classroom at West High School in a university community in the state of Iowa reveal anything about the state of writing in America? I'm not sure. But I think so.

If I can rely on my experience and my reading of public and professional journals, I think that I can transcend my immediate situation. And I think I can translate my September day and my 24 years of teaching and my work with the NCTE, the National Education Association, and the North Central Association into at least five observations.

One. <u>The teaching of writing is an exercise in discourse.</u> Just what is writing anyway? I have listened to inexperienced teachers and those who do not write give me their definitions: making an outline and then writing from it; a five paragraph paper that always has a thesis in the introduction; being conscious of mechanical errors and circling every one that is incorrect; a process that begins with outlining sentences and reviewing parts of speech. For me, writing is discourse, a complicated process that involves thinking. This thinking process includes talking, researching, coaxing what one means to the surface through writing words on paper, being aware of an audience. Experienced teachers know that writing is more than the necessary cosmetics of spelling and punctuation or the relationship of grammar to written expression.

Discourse also must ultimately answer an even more important question for our students: "Why should one want to write anyway?" Again, experienced teachers know that writing, whether it be an analysis of a short story or a 1930's-style radio script, is essentially self-expression based on experience, on a student's own perceptions and research. They know that leading students through the process of writing, from prevision to revision, will not only give young people practical skills for success on the job or in college but also will make them better learners. Writing gives students a chance to review and revise their thinking, to match in words what they are thinking. Ultimately, this process contributes to remembering.

Through discourse, my students create knowledge about themselves and thus record their personal growth. The result is a kind of human development that Henry David Thoreau once called "being alive".

Two. The teaching of writing should occur in a supportive environment. While exposure to a variety of writing modes can provide motivation, the inexperienced writer also needs continual support from both peers and the instructor. Unfortunately, most classrooms are taught by those without much formal training in the teaching of writing, often in classrooms with more students than recommended by Gene V. Glass and Mary Lee Smith of the Class Size and Instruction Project. Nevertheless, there are experienced teachers who write and know how to create supportive environments through small group activity, private conferences, positive and useful written comments, peer evaluation, and recognition through local or contest publication. These teachers know that writing is hard work with successes and failures; and they invite other authors to their classrooms to share their experience. Always they remain confident that students can write and can be helped to write better.

Three. The teaching of writing is hard work, often unrewarding drudgery, often exploited and yet criticized by those who should support it. We live in a society that delights in exploiting problems by oversimplifying them, then reacting to our oversimplifications, and finally reacting to our reactions. Such has been the case since 1975 when Newsweek hit the panic button with its cover story, "Why Johnny Can't Write". A nation, then haunted by Vietnam and Watergate, soured on the altruism of the 1960's with its belief that education could solve most of our national problems, began to find fault with the Miss Doves in the English classroom. With the graphs charting the rise of inflation and unemployment and the decline of standardized test scores, there appeared the so-called "writing crisis" which was part of a broader "back-to-basics crisis".

But some things did not change for my colleagues: bundles of themes to carry home, large class sizes, a base salary that did not rise with the cost of living, and the old burden that writing is largely the concern of the English department. Yet, some things did change: declining budgets which meant problems of attending professional meetings and conferences, fewer of our top students interested in becoming teachers, more television advertisements encouraging students to call--not write, and more book companies gearing up their old grammar books and workbooks on the cosmetics of writing. Worst of all, many of our best teachers have decided that it is time to leave the classroom. As the Chairman of the University of Iowa Education Department said recently, "How can you keep teachers who don't earn as much as refuse collectors?"

Four. <u>The teaching of writing has undergone a revolution in the past twenty years that is beginning to filter down to the classroom.</u> It seems ironic that as the misery increased so did the exciting theory and research on the teaching of writing. It is more than sad that those same teachers who feel they cannot afford an NCTE membership or a trip to a writing conference (and are often not even allowed to attend such a conference by districts that cannot afford substitutes) are just beginning to hear of the work of such educators as Janet Emig, Sondra Perl, Frank O'Hare, Linda Flower, Lee Odell, James Britton, Donald Graves, Nancy Martin, William Strong, Charles Cooper, Donald Murray, and James Moffett. However, thanks to the Carnegie Corporation and the National Endowment for the Humanities, many teachers have begun to discover the revolution in teaching writing at summer writing projects. Inspired by the 1974 Bay Area Writing Project at the University of California at Berkeley, over eighty such programs now gather teachers to write and to explore the new ideas about oral composing, dialect, free writing, sexism, and holistic grading--to name a few concerns of the writing process.

Now the revolution is providing weaponry against what Frank Smith calls the twenty-two myths about writing, which include: "People who do not themselves enjoy and practice writing can teach children how to write."

Five. <u>The computer is a tool not fully understood by most teachers of writing.</u> The computer is largely uncharted frontier. While the 1981 NCTE <u>English Journal</u> may contain an article entitled "Electronic Editing as a Tool" and the 1982 October session of the Phoenix Southwest Writing Conference may include a presentation on "Micro-computers in the Language Arts Classroom", most English teachers still work with books, paper, pencils, pens, and chalk. My high school has six Apple II computers--for the mathematics department. We have no word processors. None of my English colleagues owns a computer or processor.

For most teachers concerned about budget, paperbacks, textbooks, and the XEROX machine, the computer is no more real than Walt Disney's TRON. And they must be forgiven for their skepticism, if not for their concern, because they have read well their Orwell, Huxley, and Vonnegut. They are concerned about machines that could replace them--or even worse destroy the supportive classroom. "Don't let them sell you an electronic workbook," they told me after I described the Pittsburgh conference. They do not understand how a computer can correct all those bundles of essays, how it can narrow a topic or create concrete support, define a student's experience, and humanly and humanely reinforce learning.

I don't know. I'm not sure. But I admit that I am afraid of losing the irreplaceable. Perhaps I can best explain my feeling by quoting a note that I recently received from a former student now at Carleton College:

> Dear Dr. Workman,
>
> I was in the bookstore and when I saw this card I couldn't resist sending it to you. I'm seriously considering sending one of these to ole J.D. himself. I even found another Salinger nut--I live in an apartment with four girls, one of whom is a Salinger freak like myself. That was the best class! I think I have yet to write a paper that I was more satisfied with than the ones I wrote for that seminar.
>
> Jennifer

Jennifer had gone through an intensive reading and writing process. She had defended her papers in front of the group and later written a hilarious parody of J.D. Salinger. She had thought about everything from Zen Buddhism to the problems of non-conformity. Will computers be able to create the depth of her experience?

Of course, I also know Phil Chu. I like him, and he writes well. I even envy his word processor, as I did those owned by three seminar students last spring. And I worry about my other students. When former FCC commissioner Nicholas Johnson visited my classroom and told my students that they had better learn about computers or be doomed, I worried about that. While I cannot see myself in Alvin Toffler's electronic cottage, I think that I am ready to ride the Third Wave. After all, I have just begun to understand the writing revolution created by my own colleagues. If computers--or anything for that matter--can enrich the lives of my children, my students, then--hey!--I am ready to listen and to learn.

CULTURAL LITERACY*

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I. The Dispersed Curriculum and the New Illiteracy

For the past twelve years I have been pursuing technical research in the teaching of reading and writing. I now wish to emerge from my closet to declare that technical research is not going to remedy the national decline in literacy that is documented in the decline of verbal scores. We already know enough about methodology to do a good job of teaching reading and writing. Of course we would profit from knowing still more about teaching methods, but even using computers, better teaching technique alone would produce only a marginal improvement in the literacy of our students. Raising their reading and writing levels will depend far less on our methods of instruction (there are many acceptable methods) than on the specific contents of our school curricula. Commonsensical as this proposition might seem to the man in the street, it is regarded as heresy by many (I hope by ever fewer) professional educators. The received and dominant view of educational specialists is that the specific materials of reading and writing instruction are interchangeable so long as they are "appropriate," and "high quality."

But consider this historical fact. The national decline in our literacy has accompanied a decline in our use of common, nationwide materials in the subject most closely connected with literacy, "English." From the 1890's to 1900 we taught in English courses what amounted to a national core curriculum. As Arthur Applebee observes in his excellent book Tradition and Reform in the Teaching of English, the following texts were used in those days in more than twenty-five per cent of our schools: "The Merchant of Venice," "Julius Caesar," "First Bunker Hill Oration," "The Sketch Book," "Evangeline," "The Vision of Sir Launfal," "Snowbound," "Macbeth," "The Lady of the Lake," "Hamlet," "The Deserted Village," Gray's "Elegy," "Thanatopsis," "As You Like It." Other widely used works will strike a resonance in those who are over fifty: "The Courtship of Miles Standish," "Il Penseroso," "Paradise Lost," "L'Allegro," "Lycidas," "Ivanhoe," "David Copperfield," "Silas Marner," etc., etc.

Then in 1901 the College Entrance Examination Board issued its first "uniform lists" of texts required to be known by students in applying to colleges. This core curriculum, though narrower, became even more widespread than the earlier canon. Lest anyone assume that I shall urge a return to

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those particular texts, let me at once deny it. By way of introducing my subject, I simply want to claim that the decline in our literacy and the decline in the commonly shared knowledge that we acquire in school are causally related facts. Why this should be so, and what we might do about it, are my twin subjects.

That a decline in our national level of literacy has occurred few will seriously doubt. The chief and decisive piece of evidence for it is the decline in verbal SAT scores among the white middle class. (This takes into account the still greater lowering of scores caused by an increased proportion of poor and minority students taking the tests.) Now scores on the verbal SAT show a high correlation with reading and writing skills that have been tested independently by other means. So, as a rough index to the literacy levels of our students, the verbal SAT is a rel le guide. That is unsurprising if we accept the point made by John Carroll and others that the verbal SAT is chiefly a vocabulary test, for no one is surprised by a correlation between a rich vocabulary and a high level of literacy. A rich vocabulary is not a purely technical or rote-learnable skill. Knowledge of words is an adjunct to knowledge of cultural realities signified by words, and to whole domains of experience to which words refer. Specific words go with specific knowledge. And when we begin to contemplate how to teach specific knowledge we are led back inexorably to the contents of the school curriculum whether or not those contents are linked, as they used to be, to specific texts.

From the start of our national life, the school curriculum has been an especially important formative element of our national culture. In the schools we not only tried to harmonize the various traditions of our parent cultures, we also wanted to strike out on our own within the dominant British heritage. Being rebellious children, we produced our own dictionary, and were destined, according to Melville, to produce our own Shakespeare. In this self-conscious job of culture-making the schools played a necessary role. That was especially true in the teaching of history and English, the two subjects central to culture-making. In the nineteenth century we held national conferences on school curricula. We formed The College Board, which created the "uniform lists" already referred to. The dominant symbol for the role of the school was the symbol of the melting pot.

But from early times we have also resisted this narrow uniformity in our culture. The symbol of the melting pot was opposed by the symbol of the ste pot, where our national ingredients kept their individual characteristics and contributed to the flavor and vitality of the whole. That is the doctrine of pluralism. It has now become the dominant doctrine in our schools, especially in those subjects, English and History, which are closest to culture-making. In math and science, by contrast, there is wide agreement about the contents of a common curriculum. But in English courses, diversity and pluralism now reign without challenge. I am persuaded that if we want to achieve a more literate culture than we now have, we shall need to restore the balance between these two equally American traditions of unity and diversity. We shall need to restore certain common contents to the humanistic side of the school curriculum. But before we can make much headway in that direction, we shall also need to modify the now dominant educational principle which holds that any suitable materials of instruction can be used to teach the skills of reading and writing. I call this the doctrine of educational formalism.

II. Formalism and Pluralism in the Schools

The current curriculum guide to the study of Engish in the State of California is a remarkable document. In its several pages of advice to teachers I do not find the title of a single recommended work. Such "curricular guides" are produced on the theory that the actual contents of English courses are simply vehicles for inculcating formal skills, and that contents can be left to local choice. But wouldn't even a dyed-in-the-wool formalist concede that teachers might be saved time if some merely illustrative, non-compulsory titles were listed? Of course; but another doctrine, in alliance with formalism, conspires against even that concession to content--the doctrine of pluralism. An illustrative list put out by the state would imply official sanction of the cultural and ideological values expressed by the works on the list. The California Education Department is not in the business of imposing cultures and ideologies. Its business is to inculcate "skills" and "positive self-concepts", regardless of the students' cultural background. The contents of English should be left to local communities.

This is an attractive theory to educators in those places where spokesmen for minority cultures are especially vocal in their attack on the melting-pot idea. That concept, they say, is nothing but cultural imperialism (true), that submerges cultural identities (true), and gives minority children a sense of inferiority (often true). In recent years such attitudes have led to attacks on teaching school courses exclusively in standard English; in the bilingual movement (really a monolingual movement) it has led to attacks on an exclusive use of the English language for instruction. This kind of political pressure has encouraged a retreat to the extreme and untenable educational formalism reflected in the California curriculum guide.

What the current controversies have really demonstrated is a truth that is quite contrary to the spirit of neutrality implied by educational formalism. Literacy is not just a formal skill; it is also a political decision. The decision to want a literate society is a value-laden one that carries costs as well as advantages. English teachers by profession are committed to the ideology of literacy. They cannot successfully avoid the political implications of that ideology by hiding behind the skirts of methodology and research. Literacy implies specific contents as well as formal skills. Extreme formalism is misleading and evasive. I wish now to illustrate that point with some specific examples.

III. The Limitations of Formalism

During most of the time that I was pursuing research in literacy I was, like others in the field, a confirmed formalist. In 1977 I came out with a book on the subject, The Philosophy of Composition, that was entirely formalistic in outlook. One of my arguments, for instance, was that the effectiveness of English prose as an instrument of communication gradually increased, after the invention of printing, through a trial and error process which slowly uncovered some of the psycholinguistic principles of efficient communication in prose. I suggested that Freshmen could learn in a semester what earlier writers had taken centuries to achieve, if they were directly taught those underlying psycholinguistic principles. (With respect to certain formal structures of clauses, this idea still seems valid.) I predicted further that we could learn how to teach those formal principles still more effectively if we pursued appropriately controlled pedagogical research.

So intent was I upon this idea that I undertook some arduous research into one of the most important aspects of writing pedagogy--evaluation. After all, in order to decide upon the best methods of inculcating the skills of writing, it was essential to evaluate the results of using the different teaching methods. For that, we needed non-arbitrary, reliable techniques for evaluating student writing. In my book I had made some suggestions about how we might do this, and those ideas seemed cogent enough to an NEH panel to get me a grant to go forward with the research. For about two years I was deeply engaged in this work. It was this detailed engagement with the realities of reading and writing under controlled conditions that caused me finally to abandon my formalistic assumptions. (Later on I discovered that experimentation on a much bigger scale had brought Richard C. Anderson, the premier scholar in reading research, to similar conclusions.)

The experiments that changed my mind were, briefly, these. To get a non-arbitrary evaluation of writing, we decided to base our evaluations on actual audience effects. We devised a way of comparing the effects of a well-written and badly written version of the same paper. Our method was to pair off two large groups of readers (about a hundred in each group), each of whom when given the <u>same</u> piece of writing would read it collectively with the same speed and comprehension. In other words, we matched the reading skills of these two large groups. Then, when one group was given a good version and the other given a degraded version, we measured the overall effect of these stylistic differences on speed and accuracy of comprehension. To our delight, we discovered that good style did make an appreciable difference, and that the degree of difference was replicable and predictable. So far so good. But what became very disconcerting about these results is that they came out properly only when the subject matters of the papers were highly familiar to our audiences. When, later in the experiments, we introduced unfamiliar materials, the results were not only messy, they were "counterintuitive," the term of art for results that go against one's expectations. (Real scientists generally like to get counterintuitive results, but we were not altogether disinterested onlookers, and were dismayed.) For, what we discovered was that good writing makes very little difference when the subject is unfamiliar. We English teachers tend to believe that a good style is all the more helpful when the content is difficult, but it turns out that we are wrong. The reasons for this unexpected result are complex, and I will not pause to discuss them at length, since the important issues lie elsewhere.

Briefly, good style contributes little to our reading of unfamiliar material because we must continually backtrack to test out different hypotheses about what is being meant or referred to. Thus, a reader of a text about Grant and Lee who is unsure just who Grant and Lee are would have to get clues from later parts of the text, and then go back to re-read earlier parts in the light of surer conjectures. This trial-and-error backtracking with unfamiliar material is so much more time-consuming than the delays caused by a bad style that style begins to lose its importance as a factor in reading unfamiliar material. The contribution of style in such cases can no longer be measured with statistical confidence.

The significance of this result was, first of all, that one cannot, even in principle, base writing evaluations on audience effects--the only non-arbitrary principle that makes any sense. The reading skill of an audience is not a constant against which prose can be reliably measured. Audience reading-skills vary unpredictably with the subject matter of the text. Although we were trying to measure our prose samples with the yardstick of paired audiences, the contrary had in effect occurred; our carefully contrived prose samples were measuring the background knowledge of our audiences. For instance, if the subject of a text was "Friendship," all audience pairs everywhere we gave the trials exhibited the same differentials. Also, for all audiences, if the subject was "Hegel's Metaphysics", the differential between good and bad writing tended to disappear. Also, so long as we used university audiences* a text on "Grant and Lee" gave the same sort of appropriate results as did a text on "Friendship". But for one Community College audience (in Richmond, Virginia!) "Grant and Lee" turned out to be as unfamiliar as "Hegel's Metaphysics"--a complacency-shattering result.

While the variability of reading skills within the same person was making itself disconcertingly known to me, I learned that similar variability was showing up in formal <u>writing</u> skills--and for the same reason. Researchers at the City University of New York were finding that when a topic is unfamiliar, writing skill declines in all of its dimensions--including grammar and spelling!--not to mention sentence structure, parallelism, unity, focus, and other skills taught in writing courses. One part of the explanation for such results is that we all have limited attention space, and cannot pay much heed to form when we are devoting a lot of our attention to unfamiliar content. But another part of the explanation is more interesting. Part of our skill in reading and in writing is skill not just with linguistic structures but with words. Words are not purely formal counters of language; they represent large underlying domains of content. Part of language skill is content-skill. As Apeneck Sweeney profoundly observed: "I gotta use words when I talk to you."

When I therefore assert that reading and writing skills are content-bound, I mean also to make the corollary assertion that important aspects of reading and writing skills are <u>not</u> transferable. The content-indifferent, how-to approach to literacy skills is enormously oversimplified. As my final example of this, I shall mention an ingenious experiment conducted by Richard C. Anderson and his colleagues at the University of Illinois. It too was an experiment with paired audiences and paired texts. The texts were two letters, each describing a wedding, each of similar length, word-familiarity, sentence complexity, and number of idea units. Each audience group was similarly paired according to age, educational level, marital status, sex, professional specialty, etc. Structurally speaking, the texts were similar and the audiences were similar. The crucial variables were these: one letter described a wedding in America, the other a wedding in India. One audience was American, the other Indian. Both audiences read both letters. The results were that the reading skills of the two groups--their speed and accuracy of comprehension--were very different in reading the two linguistically similar letters. The Americans read about an American wedding skillfully, accurately and with good recall. They did poorly with the letter about the Indian wedding. The reverse was the case with the group of Indian readers. Anderson and his colleagues concluded that reading is not just a linguistic skill, but involves translinguistic knowledge beyond the abstract sense of words. They suggested that reading involves both "linguistic-schemata" (systems of expectation) and "content-schemata" as well. In short, the assumptions of educational formalism are incorrect.

IV. The Concept of Cultural Literacy

Every writer is aware that the subtlety and complexity of what can be conveyed in writing depends on the amount of relevant tacit knowledge that can be assumed by readers. As psycholinguists have shown, the explicitly stated words on the page often represent the smaller part of the literary transaction. Some of this assumed knowledge involves such matters as generic conventions, i.e., what to expect in a business letter, a technical report, a detective story, etc. An equally significant part of the assumed knowledge--often a more significant part--concerns tacit knowledge of the experiential realities embraced by the discourse. Not only have I gotta use words to talk to you, I gotta assume you know something about what I am saying. If I had to start from scratch, I couldn't start at all.

We adjust for this in the most casual talk. It has been shown that we always explain ourselves more fully to strangers than to intimates. But, when the strangers being addressed are some unknown collectively to whom we are writing, how much shall we then need to explain? This was one of the most difficult authorial problems that arose with the advent of printing and mass literacy. Later on, in the eighteenth century, Dr. Johnson confidently assumed he could predict the knowledge possessed by a personage whom he called "the common reader." Some such construct is a necessary fiction for every writer in every literate culture and sub-culture. Even a writer for an astrophysics journal must assume a "common reader" for the sub-culture being addressed. A newspaper writer must also assume a "common reader" but for a much bigger part of the culture, perhaps for the literate culture as a whole. In our own culture, Jefferson wanted to create a highly informed "common reader," and he must have assumed the real existence of such a personage when he said he would prefer newspapers without government to government without newspapers. But, without appropriate, tacitly shared background knowledge, people cannot understand newspapers. A certain extent of shared, canonical knowledge is inherently necessary to a literate democracy.

For this canonical information I have proposed the term "cultural literacy." It is the translinguistic knowledge on which linguistic literacy depends. You cannot have the one without the other. Teachers of foreign languages are aware of this interdependency between linguistic proficiency and translinguistic, cultural knowledge. To get very far in reading or writing French, a student must come to know facets of French culture quite different from his own. By the same token, American children learning to read and write English get instruction in aspects of their own national culture that are as foreign to them as French.

National culture always has this "foreignness" with respect to family culture alone. School materials contain unfamiliar materials that promote the "acculturation" which is a universal part of growing up in any tribe or nation. Acculturation into a national literate culture might be defined as learning what the "common reader" of a newspaper in a literate culture could be expected to know. That would include knowledge of certain values (whether or not one accepted them), and knowledge of such things as (for example) the First Amendment, Grant and Lee, and DNA. In our own culture, what should these contents be? Surely our answer to that should partly define our school curriculum. Acculturation into a literate culture (the minimal aim of schooling--we should aim still higher) could be defined as the gaining of cultural literacy.

Such canonical knowledge could not be fixed once and for all. "Grant and Lee" could not have been part of it in 1840, nor "DNA" in 1940. The canon changeth. And in our media-paced era, it might change from month to month--faster at the edges, more slowly at the center, and some of its contents would be connected to events beyond our control. But much of it is within our control, and is part of our traditional task of culture-making. One reassuring feature of our responsibilities as makers of culture is the implicit and automatic character of most canonical cultural knowledge; we get it through the pores. Another reassuring aspect is its vagueness. How much do I really have to know about DNA in order to comprehend a newspaper text directed to the common reader? Not much. Such vagueness in our background knowledge is a feature of cultural literacy that Hilary Putnam has analyzed brilliantly as "the division of linguistic labor." An immensely literate person, Putnam claims that he does not know the difference between a beech tree and an elm. Still, when reading those words he gets along acceptably well because he knows that under the division of linguistic labor somebody in the culture could supply more precise knowledge if it should be needed. Putnam's observation suggests that the school curriculum can be vague enough to leave plenty of room for local choice regarding what things shall be studied in detail, and what things shall be touched on just far enough to get us by. This vagueness in cultural literacy permits a reasonable compromise between lock-step, Napoleonic prescription of texts on the one side, and extreme laissez-faire pluralism on the other. Between these two extremes we have a national responsibility to take stock of the contents of schooling.

V. Cultural Literacy and Politics

Although I have argued that literate society depends upon shared information, I have said little about what that information should be. That is chiefly a political question. Estimable cultures exist that are ignorant of Shakespeare and the First Amendment. Indeed, estimable cultures exist that are entirely ignorant of reading and writing. On the other hand, no culture exists that is ignorant of its own traditions. In a literate society, culture and cultural literacy are nearly synonymous terms. American culture, always large and heterogeneous, and increasingly lacking a common acculturative curriculum, is perhaps getting fragmented enough to lose its coherence as a culture. Television is perhaps our only national curriculum, despite the justified complaints against it as a partial cause of the literacy decline. My hunch is that this complaint is overstated. The decline in literacy skills, I have suggested, is mainly a result of cultural fragmentation. Within black culture, for instance, blacks are more literate than whites, a point that was demonstrated by Robert A. Williams, as I learned from a recent article on the SAT by Jay Amberg. (American Scholar, Autumn 1982.) The big political question that has to be decided first of all is whether we want a broadly literate culture which unites our cultural fragments enough to allow us to write to one another, and read what our fellow citizens have written. Our traditional, Jeffersonian answer has been "yes." But even if that political decision remains the dominant one, as I very much hope, we still face the much more difficult political decision of choosing the contents of cultural literacy.

The answer to this question is not going to be supplied by theoretical speculation and educational research. It will be worked out, if at all, by discussion, argument, and compromise. Professional educators have understandably avoided this political arena. Indeed, educators should not be the chief deciders of so momentous an issue as the canonical contents of our culture. Within a democracy, educational technicians do not want and should not be awarded the function that Plato reserved for Philosopher Kings. But who is making such decisions at a national level? Nobody, I fear, because we are transfixed by the twin doctrines of pluralism and formalism.

Having made this technical point where I have some expertise, I must leave any pretense of authority, except as a parent and citizen. The question of guidance for our national school curriculum is a political question on which I have only a citizen's opinion. For my own part, I wish we could have a National Board of Education on the pattern of the New York State Board of Regents--our most successful and admirable body for educational leadership. This imposing body of practical idealists is insulated by law from short-term demogogic pressures. It is a pluralistic group, too, with representation for minority as well as majority cultures. Its influence for good may be gauged by comparing the patterns of SAT scores in New York with those in California, two otherwise comparable states. To give just one example of the Regents' leadership in the field of writing, they have instituted a requirement that no New Yorker can receive a high school diploma before passing a statewide writing test that requires three types of prose composition.

Of course I am aware that the New York Regents have powers that no National Board in this country could possibly gain. But what a National Board could hope to achieve would be the respect of the country, a respect that could give it genuine influence over our schools. Such influence, based on leadership rather than compulsion, would be quite consistent with our federalist and pluralist principles. The Board, for instance, could present broad lists of suggested literary works for the different grades, lists broad enough to yield local freedom, but also yield a measure of commonality in our literary heritage. The teachers whom I know, while valuing their independence, are eager for intelligent guidance in such matters.

But I doubt that such a curriculum Board would ever be established in this country. So strong is our suspicion of anything like a central "ministry of culture" that the Board is probably not a politically feasible idea. But perhaps a consortium of universities, or of national associations, or of foundations could make ongoing recommendations that arise from broadly based discussions of the national curriculum.

In any case, we need leadership at the national level, and we need specific guidance.

It would be useful, for instance, to have guidance about the <u>words</u> that high school graduates ought to know--a lexicon that would include not just ordinary dictionary words, but would also include proper names, important phrases, and conventions. Nobody likes word lists as objects of instruction; for one thing, they don't work. But I am not thinking of such a lexicon as an object of instruction. I am thinking of it rather as a guide to objects of instruction. Take the phrase "First Amendment," for instance. That is a lexical item that can hardly be used without bringing in a lot of associated information. Just what <u>are</u> the words and phrases that our school graduates should know? Right now, this seems to be decided by the makers of the SAT, which is, as I have mentioned, chiefly a vocabulary test. The educational technicians who choose the words that appear on the SAT are already the implicit makers of our national curriculum. Is then the Educational Testing Service our hidden National Board of Education? Does it sponsor our hidden national curriculum? If so, the ETS is rather to be praised than blamed. For, if we wish to raise our national level of literacy, a hidden national curriculum is far better than no curriculum at all.

How can computers help in raising our national level of literacy? I have suggested that they will help very little if they are used merely as skill-enhancing devices. But they could help a lot if they are used as knowledge-enhancing devices as well. They could, for instance, give teachers quick access to first-rate course materials on canonical subjects. They could bring into being George Miller's wonderful idea of an automated dictionary. This could do more than just show an aardvark eating termites and doing other things that aardvarks do. Suppose a student asked his computer to define "The First Amendment" (which, by the way, is not so listed in either <u>The Columbia Encyclopedia</u> or <u>The American Heritage Dictionary</u>). He might get a twenty-word definition, and a quotation of a typical use. The machine might then ask "BRANCH DEEPER?" and if the student said "Yes," he then might get a brief history of the Bill of Rights, along with a select, up-to-date bibliography. In a utopian world to which we surely could arrive, the machine might offer to branch still deeper. But before that day arrived, we would want to be sure that at least the key canonical words, phrases, and proper names had been put effectively into the data bank, at a depth of two branchings. What a tremendous labor that would be! But what potential benefits it could bring to our system of education!

Where does this leave us? What issues are raised? If I am right in my interpretation of the evidence (and I have seen no alternative interpretation in the literature) then we can only raise our reading and writing skills significantly by consciously defining and extending our cultural literacy. And yet our current national effort in the schools is largely premised on a culturally neutral, skills-approach to reading and writing. Should we insert terms like "Grant and Lee," "DNA," "The First Amendment" into the SAT test? Should we re-examine the whole humanistic side of our educational enterprise in the schools? Do we really want a twentieth-century literate democracy that corresponds to an eighteenth-century Jeffersonian vision? The reader will forgive me if I get scared in contemplating the number and power of those educators whose assumptions I may have subverted, and if I feel like Dr. Johnson after he had challenged the traditional unities of the drama:

> I am almost frightened at my own temerity; and when I estimate the fame and the strength of those that maintain the contrary opinion, am ready to sink down in reverential silence; as Aeneas withdrew from the defense of Troy, when he saw Neptune shaking the wall, and Juno heading the besiegers.

Exploiting Present Opportunities of Computers in Science and Mathematics Education

Report of the Panel on Science and Mathematics Education
Frederick Reif, Chair*

Educational Needs of Today's Technological Society

The functioning of our society -- our daily lives, our jobs, our national economy and security -- all depend increasingly on scientific and technological knowledge. Furthermore, many new information technologies (computers, various video technologies, sophisticated communication technologies,...) are increasingly permeating our society and transforming our lives. Indeed, we are witnessing the beginnings of a second industrial revolution which is proliferating machines that process information -- in the same way as the first industrial revolution proliferated machines doing mechanical work. The implications are likely to be as far-reaching.

Serious attention must, therefore, be given to the following question: How can our educational system cope successfully with our increasingly scientific and technological society?

Needs and Challenges

There are obvious, but urgent, needs to prepare all people to function adequately in the technological society in which they will have to live and work. A sufficient number of such people must be highly educated to become the scientists or engineers who can advance knowledge and provide the innovations required by our industries. A much larger number must be educated to construct, service, and use the technological devices pervading our society. And all must be educated to achieve at least a minimal level of "scientific and technological literacy", i.e., the knowledge needed to deal adequately with the manifestations of science or technology in daily life -- and, as citizens, to make adequately intelligent decisions about important human affairs affected by scientific or technological considerations.

Meeting these needs is particularly difficult because scientific and technological advances have markedly changed the nature of knowledge in our time. (a) This knowledge is becoming so extensive and super-abundant that one may rightfully talk about a "knowledge explosion". (b) The knowledge is very rapidly changing. Thus there are today many fields where people may become obsolete in a few years unless they keep on learning new information and skills. (c) The knowledge is increasingly abstract and highly symbolic. For example, the machines of a few decades ago (e.g., engines or automobiles) had levers and gears which could readily be seen and touched; but the information machines of today (e.g., computers or television) function because of invisible electrons, electro-magnetic fields, or other abstract concepts.

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In former times most people could cope with available knowledge by remembering useful factual information and applying it in fairly standard ways. But this is no longer sufficient today when knowledge is so abundant, rapidly changing, and abstract. Coping successfully with such knowledge requires judicious decision-making to select pertinent information from vast amounts of knowledge, skills of abstract reasoning, problem-solving skills for dealing flexibly with diverse or new situations, and skills of independent learning needed to acquire and apply new knowledge. These are all highly sophisticated intellectual skills, much more demanding than the remembering of factual information. Teaching such intellectual skills effectively is a major educational challenge and one difficult to achieve. Yet it is a challenge which must be addressed if people are to be prepared to function adequately in our technological society.

Major dangers loom ahead if these educational needs and challenges are not adequately met. Individual persons, unable to cope effectively with a scientific and technological society, are in increasing danger of becoming obsolete, unemployable, and marginal in the society. Furthermore, if our nation is unable to cope effectively, it is in danger of becoming economically less viable and productive, losing out to foreign competition, jeopardizing its security, and imperiling a democratic system dependent upon a well-educated population.

Existing Educational Difficulties

The preceding educational needs and challenges contrast sharply with existing actualities. In many ways current educational systems and practices are deficient in meeting our society's needs in an increasingly technological world.

Indeed, there is a growing awareness of present educational inadequacies. For example, a recent report prepared by a special commission of the National Science Board (the policy-making body of the National Science Foundation) asserts that "We appear to be raising a generation of Americans, many of whom lack the understanding and the skills to participate fully in the technological world in which they live and work.... The current and increasing shortage of citizens adequately prepared by their education to take on the tasks needed for the development of our economy, our culture, and our security is rightly called a crisis by leaders in academe, business, and government."[1] Even the popular press has displayed increasing concern about current deficiencies in science and mathematics education. For example, a recent issue of TIME Magazine states that "the U.S. is rapidly becoming a high-tech society with low-tech education."[2]

The difficulties extend considerably beyond students' inadequate exposure to scientific or mathematical subject matter.

(1) The knowledge and skills taught in schools often do not adequately reflect changing circumstances and correspondingly changing student needs. Furthermore, most attention is focused on conveying factual information, but few systematic attempts are made to teach centrally important intellectual skills such as reasoning, problem solving, or independent learning.

(2) Current teaching is often fairly ineffective and inefficient. For instance, studies have shown that, even after nominally good performance in science courses, students may emerge with rather superficial understanding. For example, such students often display gross misconceptions of scientific concepts and may be quite unable to apply their knowledge in real situations.

(3) Current teaching methods are largely based on intuitive notions and rules of thumb, rather than on systematic design exploiting reliable theoretical principles. In short, even when scientific topics are being taught, the teaching methods used are quite unscientific (strikingly different from the systematic and principled methods used to approach scientific or engineering tasks).

(4) There is a marked shortage of educational resources. In particular, there is an increasing shortage of adequately qualified science and mathematics teachers in primary and secondary schools. Furthermore, many of these teachers are over-worked, are burdened with time-consuming administrative tasks, and have neither sufficient time nor opportunities to upgrade their knowledge or improve their productivity.

(5) Access to adequate educational opportunities is difficult for some students because of their geographical location (e.g., in rural districts), individual handicaps, or other special personal circumstances.

Present Educational Opportunities

Educational Potentialities of Recent Technological and Scientific Advances

Although the growth of science and technology is at the root of many of our educational problems, recent advances in some technologies and scientific disciplines offer promising opportunities for solving some of these problems.

Recent years have witnessed impressive advances in computers and other information technologies (such as video-recorders, video discs, and new communication technologies). These technologies have become enormously more powerful, cheaper, and more widespread throughout our society. In particular, as a result of impressive advances in VLSI (very-large-scale integrated) electronics, the last few years have seen the development of microcomputers and their rapid spread into homes, businesses, and schools. It is almost certain that these developments will continue. Thus one can expect that, within the next few years, powerful microcomputers, having capabilities similar to those of large-scale computers now available only in universities and major businesses, will become available and cheap enough to be owned by individuals and schools.[3] Such microcomputers will also increasingly be used in conjunction with other information technologies (e.g., with communication technologies to interconnect microcomputers, and with video-discs to store visual or other information).

Recent years have also witnessed impressive advances in the psychology of human information processing, artificial intelligence (the science of designing computers capable of performing tasks exhibiting human-like

Computers provide powerful intellectual tools for calculating, for the word processing involved in writing, for designing technological artifacts or artistic creations, etc. These potentialities can be exploited to shift educational emphasis from the teaching of routine skills to the teaching of more sophisticated thinking skills of the kind increasingly important in our technological society.

Computers can be used to design special "learning environments" which can significantly foster student learning even in the absence of any formal instruction. In such environments students may perform simulated experiments inexpensively and without danger to themselves, they can explore independently to discover important new ideas, and they can "learn by doing" in contexts carefully adapted to their current capabilities.

Computers can be used to act as private non-human tutors, available to any student at any time or place of his or her choice. They can be flexibly adapted to the student's individual capabilities and rate of learning. They have "personality characteristics" facilitating learning, e.g., they can be very patient and engagingly motivating, without being intimidating or embarrassing. Most important, they can be superb teachers (sometimes superior to human teachers) if the teaching programs incorporated in the computers have originally been designed by the best available talent investing extensive time and effort in the preparation of the teaching programs. Finally, by incorporating recent techniques of artificial intelligence, computers can increasingly act as non-human tutors with genuine subject-matter expertise and human-like intelligence.

Computers can potentially be used to provide detailed diagnostic information about an individual student's currently existing knowlege, thinking skills, and learning capabilties. Such diagnostic information can greatly help teachers and students to devise appropriate activities for teaching or learning.

Finally, computers, used in conjunction with modern communication technologies, can be connected together into networks whereby individuals may readily communicate and interact with each other. Thus it is possible to create intellectual communities transcending the limits imposed by spatial proximity. For instance, students who are in some ways special (because of special interests, special giftedness, or special handicaps) could interact closely with similar students in remote schools or homes ---and might thus overcome the sense of isolation felt by them because of their special status in their own school.

When all the preceding capabilities of computers are used in combination, they offer the promise of outstanding educational effectiveness. (Some of these capabilities will be discussed in greater detail in a later section dealing with prototype development.)

Powerful means of educational distribution. Computers can be very effective agents for distributing good education on a large scale.

Educational programs and methods incorporated in computers can penetrate almost everywhere, especially as computers become increasingly widespread intelligence), linguistics, and related fields. Very recently these sciences have coalesced into a new interdisciplinary field of "cognitive science" dedicated to the detailed study of the thought processes of humans or computers. Cognitive science is investigating complex thought processes more systematically than traditional psychology, is providing powerful new modes of analysis and experimental methods, has led to valuable theoretical insights, and has attracted some good talent to work in this field.

These technological advances in computers and other information technologies, combined with new insights from cognitive science, presently offer some unique opportunities with far-reaching practical implications. In particular, there exist prospects of developing an applied science of human thought processes, or "human knowledge engineering", capable of improving human thought processes and designing more effective ways of using knowledge. (For example, such knowledge engineering is being successfully applied to tackle the formidable intellectual problems encountered in the design of complex very-large-scale-integrated electronics.[4]) Correspondingly, there also exist promising opportunties of more scientific and technological approaches to education, particularly in science or mathematics where complex symbolic thought processes are of utmost importance.

Such innovative approaches to education, exploiting new information technologies and building upon new insights about human thought processes, could potentially go a long way toward making education more effective and meeting the educational needs discussed in the preceding section. Indeed, these educational needs are too severe to be met by traditional approaches which focused predominantly on curricular innovation and teacher training. But more scientific and technological approaches to education offer the hope of teaching sufficiently many students the sophisticated intellectual skills required to cope with our technological society.

The next few sections outline more specifically some of the promising educational opportunities offered by computers and other information technologies, by the scientific analysis of human thought processes, and by correspondingly new approaches to educational delivery.

Potentialities of Computers and other Information Technolgies

The following are some of the major educational opportunities made possible by the judicious exploitation of presently available computers, used alone or in conjunction with other new information technologies.

Versatile media of instruction. Computers provide instructional media potentially more flexible and effective than books, movies, audio or video tapes, or other media. In particular, they can be used interactively, presenting information as well as reacting appropriately to questions posed by students. They can involve students very actively in their own learning. They can also be readily adapted to the differing needs of individual students.

Powerful teaching capabilities. Computers have some unique teaching capabilities that can be practically exploited to achieve great educational effectiveness.

throughout our society. Such educational programs may be used effectively not only in schools, but also in less formal environments such as homes, offices, museums, community centers, etc. They can greatly help and supplement human teachers, but may be quite effective even in the absence of such teachers.

Computers can potentially make excellent instruction available to all students. This can be achieved _if_ the teaching programs incorporated in the computers are designed by first-rate talent devoting extensive time and effort to the preparation and testing of such programs. As a result of such large initial investments in program preparation, the quality of teaching available to the majority of students can become appreciably better than that currently available through teachers who often lack adequate time or superior expertise.

Finally, instruction prepared for delivery by computers can be repeatedly used, readily modified, and cumulatively improved to remedy observed deficiencies or to reflect changing circumstances.

Promotion of greater scientific literacy. The increasingly widespread availability of computers is likely to foster greater popular interest in the uses of computers--and thus also to enhance people's motivation to understand the quantitative and analytical modes of thinking required for the effective use of computers. Such motivation can potentially be exploited by deliberately designing computers to be readily usable by people in all walks of life, to provide such people with appealing opportunities to engage in quantitative thinking, and thus to promote greater mathematical and scientific literacy.

Facilitation of teachers' administrative tasks. Computers can greatly facilitate many of the burdensome record-keeping and administrative tasks carried out by teachers. The valuable time freed in this way could fruitfully be used by teachers for less routine and more productive educational activities.

Tools for educational research. Computers can be powerful tools for research in education. For example, recent years have seen very fruitful applications of computers in basic studies of human thought processes relevant to education.

Important cautions. The educational potentialities of computer and other information technologies can be realized only if these technologies are used with careful educational design based on adequate theoretical understanding. As pointed out before, current teaching methods are often fairly primitive, unprincipled, and ineffective. Hence the mere use of such teaching methods with new computer technologies can _not_ be expected to lead to substantial educational improvements.

Real dangers exist if the preceding warning is unheeded. A primary preoccupation with technological hardware and gadgetry often leads manufacturers and technological enthusiasts to pay unduly small attention to the less visible "software" and educational design required for the effective functioning of the technology. Furthermore, flashiness and sheer novelty are often prized more, and likely to lead to quicker commercial profits, than genuine educational effectiveness which may be less immediately apparent.

Thus it is important to keep in mind that powerful technologies, unwisely used, may not only be ineffective but harmful. For example, injudicious educational uses of computers might merely spread mediocre education on a large scale.

Potentialities of the Scientific Analysis of Thought Processes

As mentioned previously, recent developments in cognitive science provide modes of analysis and insights that can be exploited for the principled design of instruction and the effective educational application of computers.

Understanding underlying thought processes. Traditional educational efforts have focused predominant attention on overtly observable behavior and products, e.g., on exhibited knowledge or on problem solutions. By contrast, recent work on cognitive science has indicated the fruitfulness of studying the underlying thought processes leading to such observable behavior or products, e.g., the thought processes leading to the flexible use of knowledge or the underlying thought processes needed for solving problems.

To gain adequate theoretical insights, underlying thought processes must be studied in sufficient detail to explain how the resulting intellectual performance is achieved. For example, in trying to understand the underlying thought processes involved in problem solving, one must specify in detail how to describe situations, how to choose useful symbolic representations, how to make judicious decisions to find a possible path toward a solution, how to organize relevant knowledge to facilitate the retrieval of appropriate information, and so forth. The validity of theoretical ideas derived from such analyses needs then to be tested by detailed observations of the thought processes of individual persons.

The elucidation of underlying thought processes is a challenging task. For example, experts in a field are often now consciously aware of the thought processes and kinds of knowledge used by them (no more than most speakers of a native language are aware of the underlying rules for forming correctly structured sentences). Indeed, a major reason why students have learning difficulties is that teachers do not teach explicitly many important thought processes and kinds of knowledge--because they themselves are not consciously aware of them.

Workers in artificial intelligence, who have tried to program computers to perform intellectual tasks exhibiting human-like intelligence, need to be very explicit in designing such programs and have thus become acutely aware of how difficult it is to elucidate underlying thought processes ordinarily outside the range of conscious human awareness. This is why recent work in artificial intelligence is relevant to psychological studies of human thought processes and to educational concerns for teaching complex intellectual skills.

Practical educational applications. An improved understanding of underlying thought processes offers promising opportunities for improving educational effectiveness. Indeed, without an adequate understanding of this kind, it is difficult to develop reliable approaches for teaching the complex intellectual skills required in mathematical or scientific fields.

As pointed out before, the scientific analysis of thought processes is beginning to be successfully applied in other fields, such as the design of complex electronic circuits[4]. There exist similar opportunities of applying such analyses to educational applications, thus achieving more principled and effective approaches to education. In particular, theoretical insights about underlying thought processes could then be deliberately exploited for the systematic design of good instruction and for well-conceived educational applications of computers.

Possibilities of New Approaches to Educational Delivery

New technological and scientific approaches to education, like those described in the last couple of sections, allow educational tasks to be approached in distinctly new ways, with potentially major social benefits. Conversely, the effective exploitation of the potentialities of computers and other new information technologies may require some distinctly new ways of approaching educational tasks.

Optimized combinations of instructional means. Traditionally most educational tasks have been implemented predominantly by human teachers in face-to-face contact with students, even when the teachers faced students in large classes and had little time to give them individual attention. But modern information technologies permit educational tasks to be approached from a more efficacious point of view. After all, effective education can today be provided not only by human teachers, but also by books, movies, audio and video technologies, and computers acting as private non-human tutors in other capacities. Each of these instructional means, including the human teacher, has some unique strengths and some appreciable limitations. Better educational effectiveness can therefore be realized by careful design which uses an optimum combination of such instructional means to attain desired educational goals.

In particular, such instructional design would judiciously aim to exploit the unique capabilities for each instructional means and try to minimize its limitations. Human teachers would then be used to maximum advantage in those situations where their unique capabilities are most valuable. But their potentialities would not be wasted on other tasks better performed by other media, nor would human teachers always necessarily play a central role in every educational task. Furthermore, education would then become less synonymous with schooling, with more education effectively provided in homes and other informal settings.

Exploitation of significant initial investments. Our present educational system still operates largely like a cottage industry, i.e., it is highly labor-intensive and uses many small-scale repetitive efforts. But computers and other new information technologies now make it realistically possible to implement alternative educational approaches which, like modern industry, involve the effective exploitation of large initial investments. In particular, large initial investments of talent, effort, and time could be made to produce high-quality educational programs which would then be incorporated in computers and other information technologies. These initial investments would then be amortized by repetitive and widespread use of these programs by many students.

The advantages resulting from such large initial investments would be similar to those achieved in modern industries where large initial capital investments are, of course, the rule. (a) Economies of scale might reduce the educational costs per student. (b) Better education could be made available to larger numbers of students, including those in remote locations and those with special problems. (c) Some important educational undertakings, of a kind and quality presently not attainable, might successfully be undertaken. The reason is that it would then be possible to invest first-rate talent in systematic development efforts extending over prolonged periods of time, with attendant opportunities for cumulative improvements. (Analogous comments can be made about modern industry which has been able to generate sophisticated products which could not possibly have been produced by a cottage industry. For example, only enormous initial investments in first-rate talent, in research and development, and in extensive production facilities allowed modern industry to produce the marvelous electronic calculators which are today so cheaply available to everyone.)

Continuing education. Our present educational system makes provisions for people's education until adulthood, but views their education as completed after that initial time. However, it is becoming increasingly necessary to provide continuing education throughout persons' entire lives so that teachers, engineers, doctors, and most other people can cope adequately with rapidly changing knowledge and thus maintain their professional competence. Computers and other modern information technologies can significantly help by making good continuing education readily available to working adults in their own homes or workplaces.

Research Needed to Realize the Opportunities

The preceding educational opportunities, made possible by recent advances in computers and cognitive science, are both promising and attainable. However, the effective realization of these opportunities is far from simple or automatic. In particular, it requires improved knowledge and understanding about some important issues, i.e., it requires appropriate research.

Indeed, the successful utilization of educational technologies will probably require scientific approaches similar to those which have proved so very successful in exploiting technologies in most other fields. In all such cases systematic approaches, based on adequate theoretical understanding, have ultimately proved far more successful and cost-effective than haphazard efforts, have ensured cumulative progress and improvements, and have led to impressive practical applications. It would be very surprising if educational technologies were different in these respects.

Appropriate research, undertaken to exploit the educational applications of computers, can also help to guard against some potential dangers. In particular, it can help to avoid the discrediting of promising ideas by poor implementations, the wasting of money and other valuable resources in projects with poor pay-offs, or the use of new educational technologies in potentially harmful ways.

Two kinds of research seem predominately needed at the present time. One of these is basic research undertaken to obtain improved knowledge and understanding of some fundamental issues important for the effective educational utilization of computers. The other is applied research involving the development of good prototypes exemplifying, on a relatively small scale, particular educational applications of computers and of associated instructional methods. (Such prototypes can provide very valuable information useful for subsequent larger-scale applications.)

The distinction between basic research and more applied prototype research is not very sharp. Furthermore, these two types of research can fruitfully interact with each other. Thus basic research may often suggest theoretical ideas or methods which can best be tested in some prototype situations. Conversely, prototype research may often lead to questions or difficulties suggesting interesting basic investigations.

The important areas of needed research are those which would contribute substantially to the realization of the educational opportunities discussed in the preceding sections. At the 1982 Pittsburgh Conference on Research in Computers in Education, I and the other members of the Science and Mathematics Group of that Conference tried to identify some particular lines of research which seem most needed and promising at the present time. Our conclusions and recommendations are summarized in the next several sections. Needless to say, our suggestions represent merely our own judgment and are not meant to be exhaustive. Other lines of research might thus also be worthy of pursuit if they can be shown to be needed and likely to be fruitful.

The next section outlines some suggested lines of basic research and the subsequent section some suggested lines of prototype research. Finally, the last section recommends some ways for fostering the effective implementation of these kinds of research.

Basic Research

The basic research needed for effective educational applications of computers involves research dealing with cognitive issues (i.e., with thought and learning processes) as well as research dealing with some pertinent social issues.

Research on Cognitive Issues

Research on cognitive issues should build upon the methods of analysis and the insights derived from recent work in cognitive science (e.g., the psychology of human information processing and artificial intelligence). The ultimate aim of this research is to obtain a sufficiently detailed knowledge and understanding of complex human thought processes (of the kind encountered in scientific and technological fields) to provide a sound theoretical basis for designing effective instruction provided by means of computers, other new information technologies, or human teachers.

Thought and learning processes. It is clearly important to obtain a better understanding of the underlying thought processes needed to use scientific concepts or to solve scientific problems (especially since a major aim of education in mathematics, science, or engineering is to teach students conceptual and problem-solving skills in these fields).

One line of pertinent investigation concerns the thought processes and conceptual structures of novice students. Recent studies have revealed that students approach learning tasks with many prior conceptions, acquired in daily life, which are often remarkably resistant to change and present major obstacles to the learning of new scientific concepts. Most of these studies have been descriptive, reporting rich observations of the pre-scientific misconceptions exhibited by students. It would be useful if future studies were somewhat more theoretical and analytic, aiming to understand why students' conceptions are so resistant to change, how conceptual structures can be effectively modified, or how to predict common conceptual difficulties exhibited by students.

Another line of useful investigation concerns the underlying thought processes and forms of knowledge responsible for the good performance of experts in mathematical or scientific fields. As pointed out previously, much of this expert knowledge is "tacit", i.e., outside the range of conscious awareness of the experts themselves. Studies designed to make this knowledge more explicit are clearly important since they would lead to a better understanding of this knowledge and to more systematic ways of teaching such knowledge to students.

Another line of fruitful investigation, going beyond the study of experts, concerns the underlying thought processes and forms of knowledge leading to good human intellectual performance--without necessarily aiming to simulate the behavior of actual experts. Such studies would forgo the assumption that experts always perform optimally, could devise some thought processes superior to those of current experts, and could also design effective thought processes deliberately adapted to the limited capabilities of students. Such studies, approached from the point of view of "human knowledge engineering", could contribute substantially both to education and to the design of improved forms of human-computer interaction.

Until very recently, theories of learning dealt only with rather simple learning tasks. It is only now that, building upon newer insights into human thought processes, attempts are being made to formulate detailed theoretical models of human learning in more complex symbolic domains. Studies dealing with the formulation and testing of such learning models are obviously highly relevant to instruction, particularly in intellectually demanding fields such as science or mathematics. Indeed, studies of this kind are crucial to develop theoretically well-grounded approaches to instructional design, approaches needed to produce more effective and efficient learning (with or without computers).

Knowledge structure. Recent work in cognitive science indicates that the manner in which knowledge is structured can greatly affect the ease or difficulty of using such knowledge for various intellectual tasks. Hence it is important to understand more fully how people can organize and symbolically represent knowledge so that it is useful for remembering information, retrieving selected information relevant to a particular situation or problem, regenerating particular knowledge that has been forgotten, modifying or generalizing existing knowledge, or performing other intellectual tasks.

Studies enhancing our general understanding of these issues are also germane to more specific investigations concerned with the knowledge structures of particular scientific domains. In particular, it is becoming increasingly important to organize scientific knowledge effectively, to identify core knowledge which allows one to derive or subsume large amounts of related knowledge, and to identify what kinds of knowledge are most useful for different tasks or different kinds of students. Only in this way is it possible to be judiciously selective in what to teach and thus to help students to cope with ever-increasing scientific knowledge. Indeed, without adequate attention to effective knowledge organization, students will face increasing difficulties in attaining even minimal competence in a particular domain, and will increasingly be unable to transcend the bounds of excessively narrow specialization.

Mental models. "Mental models" are relatively simple conceptual schemes used by people to explain or predict observable phenomena encountered by them. Although such explanations and predictions may be qualitative or scientifically primitive, they can be very useful for dealing with the surrounding world and with the complex devices (automobiles, computers, ...) pervading our technological society. For example, they allow people to obtain a functional understanding of how such devices work and to troubleshoot them when they malfunction.

It would be of interest to study more extensively what particular kinds of mental models are most useful for various kinds of tasks and kinds of people. Indeed, different mental models, of various degrees of complexity and predictive power, can be formulated to deal with the same phenomenon or device. For example, significantly different mental models are useful for the designer of a car or computer, for the repairman who needs to maintain and service these devices, or the lay person who needs to use these devices in daily life.

A better understanding of mental models can have substantial educational importance since it would allow one to teach students relatively simple, but powerful, ways of thinking about complex phenomena or devices. It would thus also help in efforts to increase the scientific or technological literacy of students whose primary interests are not scientific.

Relevant research in artificial intelligence. Although artificial intelligence is primarily concerned with computers, some of the research in that field is highly germane to educational applications. (a) Because efforts to make computers behave intelligently require a great deal of explicitness and precision, they can yield valuable insights about human thought processes. (b) Work in artificial intelligence can provide very powerful tools for educational applications of computers. For example, it promises to lead to computers more readily usable by people without specialized training about computers. Hence it could greatly facilitate authoring educational programs to be implemented by computers. (c) It can help to make computers play the role of genuinely intelligent non-human tutors (in applications which have now come to be called "intelligent computer-aided instruction"). (d) It can also help in designing computers capable of diagnosing rapidly and effectively the existing knowledge or learning readiness of individual students.

Meaningful evaluation. Reliable progress in education, and the educational applications of computers, requires adequate evaluation of work undertaken in this field. The difficulty is that most past efforts at educational evaluation have not been adequately useful or cost-effective because they have focused on superficial measures, without elucidating the knowledge most important for ensuring further progress.

Studies are needed to provide more useful forms of evaluation. In particular, evaluations should be theoretically meaningful, i.e., they should provide knowledge which can improve theoretical models of thought processes or of instruction. Such improved theoretical knowledge would then provide a reliable basis for improving subsequent educational applications.

Research on Social Issues

Some research is needed on social and psychological factors affecting the introduction of new educational technologies and approaches into existing social contexts. Such research should aim to provide insights and predictive power sufficient to guide practical implementations.

Acceptance of educational innovations. Studies are needed to identify factors that lead people or institutions to resist or accept the introduction of new educational approaches or technologies. Such studies should provide improved understanding of the perceptions of teachers, students and parents--as well as adequate knowledge about cultural and social factors within present-day schools.

Knowledge of this kind could help to devise improved methods of communication and participation for modifying people's existing conceptions and facilitating their acceptance of change. For example, it would be desirable to carry out experiments where such methods are used to change the perceptions of parents and teachers about present educational needs or about the merits of new educational technologies.

Economic aspects. People are unlikely to accept new educational approaches and technologies unless they are persuaded that the entailed costs are reasonable. But meaningful comparisons of costs are subtle, particularly since the exploitation of computers in education would entail a shift from small recurrent operating costs to larger initial investments. Hence it would be desirable to have some good analyses comparing the costs and benefits of the newer educational approaches with those of more traditional ones.

Prototype Research

The judicious educational application of computers could be greatly furthered by relatively small-scale projects exemplifying useful applications of computers and serving as prototypes for subsequent deployments of educational technology on a large scale. (a) Such prototype projects can provide valuable information and theoretical insights if they are carried out carefully and treated like experiments performed under well-controlled conditions. (b) Different approaches can then be readily explored and modified. Furthermore, mistakes can be made on a relatively small scale where they are relatively harmless and where they can be more easily diagnosed or remedied. (c) A good working prototype can be very effective in persuading people to adopt new approaches, often more effective than many published articles without visible implementations.

To be useful, the development of prototypes must be undertaken in a "principled way", i.e., the design and implementation of the prototype should be guided by explicit theoretical ideas about instruction. The subsequent evaluation of the prototype should then try to elucidate <u>why</u> certain things work or do not work--and should thus contribute to the refinement of theoretical ideas useful in the future.

Prototype projects must be of high quality. Otherwise they may do more harm than good, e.g., they may discredit promising ideas by poor implementations. Thus it would be preferable to have a smaller number of high-quality prototype projects, carried out by good talent, than a larger number of projects of questionable quality.

Although prototype projects may properly want to emphasize particular technological or cognitive aspects involved in the educational applications of computers, they should pay heed to the psychological and social factors important in real contexts. Thus they should pay proper attention to motivational factors affecting student learning. They should be aware that learning may be affected by collaboration or competition between students. They should also attempt to design educational applications in a fashion that would facilitate their ultimate social acceptance and proper use.

Computers as Intellectual Tools

Computers can be powerful intellectual tools and media of expression. With the aid of the methods of artificial intelligence, they can even be genuinely intelligent agents serving people in various roles. For example, computers can do arithmetical calculations, can perform symbolic algebraic manipulations, and can construct and manipulate graphs. They can be word processors which facilitate writing, correct spelling errors, and make suggestions about improved grammatical constructions. They can act as secretaries, bookkeepers, and accountants. They can also be powerful aids for designing technological devices or works of art.

These capabilities of computers may profitably be explored in the following kinds of prototype applications.

Computers as tools for educators. Computers could potentially be used to facilitate greatly the administrative and record-keeping tasks of teachers. This rather simple application, explored in prototypical situations, might well show significant increases in the productivity of teachers, their time available to students, and their educational effectiveness. Such results would, of course, have obvious practical applications which could be readily implemented.

A more challenging task for prototype exploration is the development of computer environments designed to facilitate the authoring of computer-implemented educational applications. In particular, such computer environments should aim to make authoring possible for people with minimal experiences in computer programming. Furthermore, methods of artificial intelligence might be exploited to incorporate within computers appreciable expertise about particular subject-matter domains. The authoring of instructional materials in these domains could thereby be appreciably facilitated.

Computers as tools for students. Computers, available as tools for students, can today help them carry out many relatively simple tasks which students traditionally spent years learning to do unaided (e.g., making arithmetical computations, manipulating symbolic expressions in algebra, implementing syntax rules in computer programming,...). Various resulting implications may usefully be explored in prototype projects and associated research studies.

Some such projects should explore the extent to which such computer tools, available to students, can provide increased time and opportunities to teach such students more sophisticated intellectual skills (e.g., reasoning, problem solving,...) important in our technological society.

Other prototype projects might explore new teaching methods made possible by the existence of such computer tools. For example, traditionally one teaches predominantly "bottom-up", i.e., one teaches first simple skills (such as arithmetic computation) and then builds upon these to teach more sophisticated skills (such as solving realistically interesting problems). But the availability of computers, which can perform simple tasks for students, would allow one also to teach in reverse "top-down" fashion. Thus one could start quite early to teach problem solving or other sophisticated skills, using computers to carry out the necessary simpler tasks (such as arithmetic computations). An interest in problem solving might then afterwards be used as a motivating and facilitating context to teach students more of the simpler intellectual skills.

Such prototype efforts suggest several questions worthy of study. (a) What are the relative merits of such bottom-up or top-down teaching methods? (b) What intellectual skills are most needed by persons in a society where computers are increasingly widely available as intellectual tools? (c) What are the corresponding implications for the selection of appropriate knowledge and skills to be taught in various curricula? For example, when arithmetic computations can so readily be executed by cheap calculators practically available to everyone, is there still need to teach students great facility in numerical computation? Or might it be sufficient to teach them merely how to carry out computations in case of need, but without requiring great facility?

Learning Environments

Computers can be used to design learning environments which can foster student learning even in the absence of any formal instruction. Such learning environments have been designed for various educational levels, e.g., the LOGO computer language and "turtle geometry" for use by quite young children,[5] computer environments for learning to troubleshoot electronic circuits,[6] and others. The following kinds of prototype projects would be desirable to explore more fully the potentials of various learning environments.

Access to realistic data. Computers can provide learning environments where students have access to real data (e.g., data about populations and demographic trends, economic data about various countries,...) and can use the computer to facilitate computations with such data. Students would then no longer be restricted to working with unrealistically simplified numbers, but could work with information pertinent to realistic contexts. Such learning environments could also be exploited to teach students useful knowledge about modern computer-implemented data bases and the techniques needed to work with such data bases.

Simulated laboratories. Computers can be very profitably used to create learning environments simulating laboratory situations.

Such laboratories may simulate real situations which might be encountered in an actual laboratory. However, the simulation has the following advantages: It is usually much less expensive than a real laboratory. It allows the quick exploration of many possibilities and the systematic variation of many relevant parameters. (For example, it is possible to carry out large numbers of simulated genetics experiments without waiting weeks for real biological organisms to grow.) It allows active exploration without danger of harm to students (since simulated explosions are much more innocuous than real ones). Finally, it allows students to focus their attention on centrally important issues, without being distracted by the many logical details of real experiments.

Needless to say, such simulated laboratories are not a substitute for all real laboratory work, but may often be very good preparation for actual laboratory experiments.

Simulated laboratories also allow the exploration of phenomena outside the range of ordinary experience. For example, it is possible to explore, in simulated environments, phenomena in outer space, phenomena at very high speeds near the speed of light, or phenomena at the atomic scale.

Lastly, simulated laboratories allow the exploration of hypothetical or fictitious situations not encountered in the real world. For example, it is possible to create simulated worlds which behave according to the primitive pre-scientific conceptions of novice students. Students, left free to explore such worlds, would then quickly discover in what ways their own conceptions are not adequate to explain phenomena in the real world.

All the preceding applications could usefully be explored in prototype situations.

Learning by doing. Effective learning is greatly fostered when students are actively involved and learn by doing. Computers can provide learning environments which can markedly facilitate such active learning. For example, they can provide environments which can be simplified to facilitate a student's independent learning by discovery--and which can then gradually be made more complex to match the increasing capabilities of the student during the learning process. They can allow students to formulate hypotheses, to perform experiments in the computer environment, to analyze the results, and to use these to modify the original hypotheses. Moreover, they can afterwards exhibit to a student a record of his or her thought processes, thus helping to improve the student's intellectual performance through greater self-awareness of his or her own thinking and learning.

Development and use of mental models. Computers permit the design of learning environments which help students acquire mental models to deal with complex phenomena or devices. For example, the simulated manipulation of switches can be presented on a computer screen by corresponding displays showing the corresponding flow of electrons in circuits--thus providing students with useful mental models of the functioning of electronic circuits. Similarly, the computer can help students to use alternative mental models, e.g., by displaying corresponding visual or mathematical representations of the same situation.

Computers as Tutors

As already mentioned, computers can potentially be excellent non-human tutors, available to every student and highly responsive to his or her individual needs. The potentialities are particularly large if one exploits recent methods of artificial intelligence to endow such tutors with more human-like intelligence. The non-human tutor can then have genuine expertise about the subject-matter to be taught, can use student responses to diagnose the student's knowledge and understanding at any stage, and can provide corresponding tutorial guidance. For example, such "intelligent" computer tutors or "coaches" have been constructed to teach some simple arithmetic skills (e.g., in the game of WEST), skills in electronics (SOPHIE), or skills in medical diagnosis (GUIDON).[7]

It would be desirable to have good prototype projects demonstrating the capabilities of computers as excellent tutors. Such prototypes might usefully include both some which do not invoke the methods of artificial intelligence (thus more easily constructed and also implementable on microcomputers commonly available today) and some which do use artificial intelligence (thus more powerful and suitable for microcomputers more readily available a few years from now).

The following two aims seem particularly worthy of pursuit. (a) Constructing prototype computer tutors which, by virtue of good design efforts by very good talent, can provide excellent instruction in a particular scientific domain, even without appreciable aid from human teachers. (b) Constructing such tutors which can help to teach conceptual and problem-solving skills in scientific domains of appreciable difficulty.

Diagnosis of Student Knowledge and Abilities

Computers, programmed on the basis of an adequate analysis of human cognitive processes, can be used as diagnostic devices to ascertain quickly a student's existing knowledge, understanding, misconceptions, or intellectual skills. For example, an existing computer program (BUGGY[8]) has been used, with impressive effectiveness, to detect a student's underlying arithmetical misconceptions responsible for seemingly erratic errors made by the student when adding or subtracting multiple-digit numbers.

It would be desirable to have prototype applications where computers are used as diagnosticians to help determine underlying student knowledge and intellectual skills in more complex scientific or mathematical domains. Such computer diagnosticians would make teachers more aware of the various intellectual components needed for good performance, would reveal to them which of these components are deficient in the case of any particular student, and would help uncover hidden conceptual difficulties. Such information would, of course, be very valuable for planning appropriate instruction. (The design of computers for such diagnostic purposes would probably also stimulate interesting research questions about cognitive processes.)

Intellectual Communities by Networking

Prototype projects might also explore ways of creating useful intellectual communities by means of networks of interconnected computers. Such networks would make possible beneficial communication and interaction between students with similar interests or similar special problems (e.g., between similarly handicapped or gifted students). The networks could thus create intellectual communities transcending the bounds of any particular school. Beneficial results might include greater intellectual stimulation for students, greater motivation for learning, and less psychological isolation for exceptional students in particular schools.

Networking could also be quite helpful in creating improved interaction between teacher or authors of educational programs. Furthermore, the existence of such networks might appreciably facilitate the dissemination of new educational approaches or programs.

Integrated Application of the Preceding Potentialities

Although each of the preceding educational uses of computers is promising and worthy of exploration, the combined application of these various uses in an integrated way would be particularly effective. For example, computers could be used to design a learning environment where students could explore, on their own, to discover new knowledge; would have powerful computer tools available to help this exploration; could be judiciously guided in this process by non-human tutors providing them with useful knowledge and advice; and could interact with each other through a computer network. Such an environment could, indeed, greatly facilitate effective and efficient learning.

It would be highly desirable to have prototypes where the educational potentialities of computers would be explored, in such integrated ways, to provide instruction in a particular scientific domain. The full educational capabilities of computers could then be demonstrated in particularly convincing ways.

Exploitation of Computers for Curricular Innovation

The increasingly widespread availability of computers provides opportunities for promoting and spreading educational innovations more effectively than has traditionally been the case. The implementability of these opportunities might usefully be explored in some prototype projects. For example, new educational approaches incorporated in "software" programs, distributed to microcomputers widely available in schools and homes, could affect very directly the learning of students and the perceptions of teachers. Such software, <u>if</u> sufficiently carefully designed, could thus be used to introduce more modern topics in scientific curricula, to restructure commonly taught knowledge in more modern and effective ways, or to teach more sophisticated intellectual skills (such as problem solving). These opportunities could also be exploited to promote greater scientific and computer literacy among all students and teachers.

Computers in Teacher Education

Lastly, it would be desirable to have prototype projects which adequately recognize the new role of computers in the education of teachers. (a) It is important to make teachers more familiar with computers and their use. At least, teachers must know some of the potentialities and limitations of computers encountered by them in their teaching positions, and must have a level of "computer literacy" not too inferior to that of many of their students. (b) The education of teachers should make them adequately knowledgeable about the educational application of computers, about new educational approaches made possible by computers and recent insights into human thought processes, and about new educational goals needed to prepare students to function in our technological society. (c) Finally, computers should be exploited as teaching tools in the actual education of teachers. This might not only improve the education of teachers, but also make them directly familiar with the educational applications of computers. Such familiarity is particularly important if teachers are later to exploit computers in their own teaching (since teachers tend to teach in the way in which they themselves were originally taught).

Effective Implementation of Research

The kinds of basic and prototype research discussed in the preceding sections are essential to ensure reliable progress for exploiting the educational applications of computers. However, the fruitful implementation of such research and development is not easy. The fundamental difficulty is that, while progress in computers and other information technologies has been very rapid, systematic efforts to apply these technologies for educational purposes are in their infancy. In particular, the kinds of talent needed for such efforts are in short supply, public schools are unable to undertake substantial efforts, universities are presently beset by financial difficulties and prone to view education along rather traditional lines, and business enterprises focus primarily on short-term efforts promising quick profits.

The following are a few suggestions for overcoming some of the difficulties and ensuring effective implementation of the needed research efforts.

Investing Appropriate Talent

The talent, needed to exploit the educational applications of modern information technologies and cognitive science, needs to be more analytic and scientific than much of the talent attracted to education in the past. Furthermore, this talent, like that needed to advance any other modern scientific or technological field, must be of first-rate quality. Hence it is now important to attract to education some top talent which might otherwise go into fields such as artificial intelligence, computer science, information-processing psychology, some natural science or mathematics, or some branch of engineering. (All these other fields are presently institutionally better supported, more prestigious, and financially more remunerative than education. The difficulties of attracting appropriate talent are thus appreciable.)

Successful applications of computers, to provide good education in scientific or technological fields, require many different kinds of expertise (e.g., expertise in the particular scientific or technological field to be taught, expertise in cognitive science to understand sophisticated thinking and learning processes, expertise about computers and computation, expertise about educational and graphic design, ...). It is increasingly unreasonable to expect that all these different kinds of expertise can be adequately possessed by a single person. Hence it becomes important to provide contexts where persons with different kinds of expertise can effectively collaborate in complementary fashion. Such collaboration requires more than casual interaction between persons in different disciplines. Instead, each expert in a particular field must know a substantial amount about the other relevant fields to communicate intelligently with collaborating experts in them.

Judicious Mix of Efforts

At the present stage of knowledge about the educational applications of computers, it would be unwise to focus massive research efforts along one or two directions which might possibly not be very productive. Conversely, it would be unwise to undertake so many diverse efforts that limited resources would be dissipated in efforts too small to be significant. A judicious mixture of kinds of scales of efforts thus seems most advisable.

In particular, it would seem wise to have efforts pursuing basic research as well as some implementing prototype projects. In each of these categories, it would then be useful to pursue several (although not necessarily all) of the lines of investigation suggested in the preceding sections.

Similarly, it would seem wise to support some relatively small-scale efforts which could encourage imaginative innovation and help to attract new talent. Indeed, some such small-scale projects might have large pay-offs. On the other hand, it would also be useful to mount some larger projects to ensure efforts with the critical-size resources needed to accomplish some more substantial tasks.

Educational R & D Centers

Research and development efforts directed at the educational applications of computers may often require resources beyond those available to an individual person or small group of persons. Hence we (members of the Science and Mathematics Group at the Pittsburgh Conference) strongly recommend the establishment of some R & D (research and development) centers dedicated to the furtherance of new scientific and technological approaches to education. Such a R & D center should be widely accessible to educational researchers and designers throughout the nation. Within the realm of education, it should thus play a role analogous to that of one of the national laboratories in high-energy nuclear physics (e.g., the Fermi Laboratory).

Such an educational R & D center would fulfill the following functions:
(1) It would provide the machines and supporting personnel needed to carry out work on the educational applications of modern information technologies. Expensive computers could thus be made available to individual researchers or developers who would otherwise have no access to them. (Indeed, expensive computers may be needed to design practical educational programs for student use a few years later. The reason is that the price of the same computer will by then have dropped so much as to be generally available to students.)

(2) The R & D center would provide the possibilities of fruitful collaboration between the different kinds of expertise needed to produce good educational programs (e.g., between subject-matter experts, cognitive scientists, computer programmers, workers in artificial intelligence, etc.).

(3) Such an educational R & D center should have a good permanent staff doing ongoing work of high quality. In addition (as in the case of the Fermi Lab), the center should provide a working environment for numerous talented

researchers and designers staying there for more limited periods of time. Such visitors would provide the center with an influx of new ideas and would ensure its continuing intellectual vitality. Some of the visitors would be financially supported by the Center; others would come there to work while supported from funds or grants provided to them from other sources. The work initiated by visitors could be partially continued by students or other personnel even after the visitors have left--especially by exploiting the communication facilities provided by networked computers.

(4) Teachers coming temporarily to such an educational R & D center could provide educational designers useful information about student needs and school conditions. Conversely, such teachers would learn about new educational approaches and programs--and could thus help to diffuse new knowledge and ideas to existing schools.

(5) If such an educational R & D center were close to a good university and affiliated with it, the center would also help in training the new kinds of people (teachers, developers, and researchers) needed to realize the educational opportunities of computers.

A single R & D center would run the danger of becoming unduly fixated on a single educational approach and might thus suppress alternative points of view. Furthermore, such a single center would not be conveniently accessible to visitors around the country. To ensure a healthy competition between ideas and adequate access, it would thus be desirable to have at least two such centers. One of these might predominantly be concerned with science and mathematics, the other with language skills--although no sharp separation between these interests would be desirable.

The advancement of any new field requires sufficient concentrations of good talent supported by adequate resources. If well implemented, the establishment of some educational R & D centers could advance significantly effective educational applications of computers and improved scientific approaches to education--and could thus help meet the educational needs of our technological society.

Footnotes

1. National Science Board, Commission on Precollege Education in Mathematics, Science and Technology. Today's Problems, Tomorrow's Crises, National Science Foundation Report, 1982.
2. TIME Magazine, p. 67 (27 December 1982).
3. For example, in the fall of 1982 Carnegie-Mellon University and the IBM Corporation concluded an agreement for producing, by 1986, powerful new microcomputers, with professional capabilities, capable of being purchased at affordable prices by every student at that University.
4. See, for example, M. Stefik and L. Conway. Toward the principled engineering of knowledge, AI Magazine, vol. 3, #3, pp. 4-16, Summer 1982.
5. S. Papert, Mindstorms: Children, Computers, and Powerful Ideas. Basic Books, New York, 1980. See also H. Abelson and A. diSessa, Turtle Geometry: The Computer as a Medium for Exploring Mathematics, MIT Press, Cambridge, Mass., 1981.

6. Such a computer environment, supplemented by tutorial guidance, is described by J.S. Brown, R.R. Burton, and J. deKleer. Pedagogical, natural language, and knowledge engineering techniques in SOPHIE I, II, and III. In D. Sleeman and J.S. Brown (Eds.), Intelligent Tutoring Systems, Academic Press, New York, 1982.
7. These and other applications are summarized in A. Barr and E.A. Feigenbaum. The Handbook of Artificial Intelligence, vol. 2, chapter 9. William Kaufman, Los Altos, California, 1982.
8. J.S. Brown and R.R. Burton. Diagnostic models of procedural bugs in basic mathematical skills, Cognitive Science, vol. 2, pp. 155-192, 1978. See also R.R. Burton. Diagnosing bugs in a simple procedural skills. In D. Sleeman and J.S. Brown (Eds.). Intelligent Tutoring Systems, chapter 8, Academic Press, New York, 1982.

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A Research Agenda on Computers in Education:

Report of the Panel on Reading and Writing Research

Alan Lesgold, Chair

Outline

INTRODUCTION

The computer revolution places great demands on our education systems. Americans want to be prepared for the new kinds of jobs and social roles that technology has created, and they especially want their children to be prepared for the computer era. Industrial cities around the country are undertaking cooperative plans for attracting high-technology businesses and training a work force for them. Our school systems are being asked to provide better science and mathematics education, higher levels of literacy and trainability, and specific computer skills.

This demand for excellence and for new educational forms and content comes at a time when schools face severe economic pressures. Budgets are shrinking, good teachers are abandoning education for more lucrative fields, the better students are tending not to enter the teaching profession, and a history of shrinking in-service training budgets makes special efforts to improve teaching techniques an added cost that must be considered while budgets are being further cut. The dilemma our schools face is that teachers need to learn new content and teaching methods if we are to succeed as a technological society, but school systems cannot afford to incur the increased costs involved in providing for this professional development. At a time when many teachers tell us that they make less than unskilled labor, and pay out of pocket for the pencils their students use, it is unlikely that the costs of the necessary training can be passed on to them, either.

In fact, Americans must face these costs; they are necessary to the economic defense of our country. However, it happens that the situation is not as dismal as it might appear. The very technology about which we must educate teachers has the potential for making them more productive. Several areas of science and technology have between them created the potential for using the computer to improve education, to enhance teacher productivity by performing tasks that do not require their special skills and by acting as assistants in tasks that demand more intelligence. These areas include a broad range of activities in the fields of cognitive psychology and artificial intelligence as well as the technological innovations that are making computer power, in the form of microcomputer systems, more substantial, more easily used, and more affordable. In the next few pages, we present several examples of what affordable computers could do for education in the next three to ten years and then briefly discuss the computer technology and the specific knowledge needed for these possibilities to be realized. We then turn to the basic purpose of our report, which is to indicate what role the federal government can play to catalyze local schools and the private sector into developing and deploying the many computer tools that education for a high-technology society needs.

What Is Possible?

The computer as a simulated laboratory. Recent research findings indicate that many students, even after taking a physics course, do not understand the basic mechanical principles that inter-relate force, mass, and acceleration. They do not understand Newton's Laws of Motion. Their knowledge of the physical world is stuck at the level of Aristotle while they live in the world of Einstein. In a real laboratory, the sort that physics students encounter, they can be shown the effects of forces on objects, but they misperceive those effects. Now, computer programs are available that allow students to see what would happen if their naive beliefs were true and to compare this to what happens in a world governed by Newton's Laws. After all, computer animations can illustrate events that violate the laws of physics. Further, many different viewpoints can be provided that allow attention to focus on how the student's current beliefs differ from the more standard views. In essence, the computer says, "If your beliefs were true, then this is what would happen, but in fact here is what happens instead." Programs that generate the needed animations are available for classroom use today. Programs that include a built-in tutor that could coach students through individually tailored experiments aimed at their specific levels of knowledge will be feasible in a few years.

Diagnosis of student progress in learning. While teachers have good global ideas of the relative abilities of their students, it is not uncommon for specific knowledge deficiencies in some student to be taken as sloppiness or lack of practice. A collaboration of industrial and university-based researchers has greatly improved our understanding of the different sources of mediocre performance in arithmetic, using the computer as a tool. The initial laboratory approach was to use the full power of a half-million dollar computer to analyze the answers of children to a set of subtraction problems. A computer model of the specific mental acts required to successfully do subtraction was developed. Then, the computer attempted to determine whether deleting one or two specific steps in the subtraction procedure would lead to the exact error pattern a child displayed. In about a third of the children studied, a specific knowledge deficiency was detected that was the cause of a child's problems. Experienced teachers could not detect these weaknesses and would have simply kept asking the children to practice their incomplete skills--to practice doing subtraction incorrectly. The diagnosis program has now been reduced to fit onto microcomputers that many schools already own. Within a few years, using more powerful microcomputers, it can be possible for the computer not only to detect missing knowledge in arithmetic but even to provide some hints to the student that allow discovery of the missing steps that would result in correct performance.

Networks to improve literacy. We can imagine an exciting environment in which students use advanced personal computer systems to access books in distant libraries, to send mail to their classmates providing them with feedback on their latest essays, and to obtain advice from an automated tutor about how to improve their reading and writing skills. Their teacher could use computer tools to diagnose individual students' difficulties quickly and to develop appropriate material and intervention strategies. In such a classroom, the natural use of the written word to find out about the world and to interact with other children would result in integrated learning of reading and writing skills. Pieces of this world already exist. Putting the pieces together and making such possibilities accessible to teachers will require some hard work.

What Is Needed?

These exciting possibilities will require more powerful computer systems. However, we have experienced a continual decline in the price of computer power, with prices of different components continuing to drop one-fifth to one-third in price each year. Expert advice is that these price drops will continue for some time, long enough to assure that schools' current levels of computer investments will within this decade be sufficient to buy machines powerful enough to allow intelligent instructional systems to operate in our classrooms and in many homes.

Our concern is with what will not happen automatically. The possibilities described in the previous section are based upon our knowledge of recent developments in artificial intelligence and other areas of computer science, in the cognitive psychology of instruction, and in computer technology. However, more work is needed for these possibilities to be fully realized. The basic advice of this conference is that striking improvement in the quality and productivity of instructional computer systems appears to be attainable but will not come to pass without a national investment.

Considerable software is being developed at the cottage industry level, at little risk to publishers and other school suppliers, who pay only royalties on actual sales. Most of this software consists of modest extensions of old programmed instruction techniques and video presentations of existing workbook pages. Swamped by the new world of computers, school administrators and teachers are so impressed and challenged by even these weak products that little is required to successfully market them. In contrast, the development of significant intelligent computer tools for education will be expensive and risky. Why should businessmen exchange a sure profit on the mediocre for a risky effort after excellence? Left to grow on the basis of market forces, the world of computers in schools is likely to involve classrooms containing students who are isolated from each other by electronics, bored or confused by poorly designed software, and rendered passive by systems which do not promote exploration or initiative.

We ask the federal government to take some of the intitial risks and to make a market for excellence in computer-based education. Specifically, we recommend the following:

> The federal government should fund a coherent effort to develop prototypes of the intelligent instructional systems we believe are possible. Such prototypes can act as guides for private industry and also as laboratories for needed research on the specific processes involved in skilled reading, writing, mathematics, and other intellectual performances, new ways to adapt to individual differences in aptitudes and progress in learning, and the applied psychology of student and teacher interaction with automated instructional systems. They would also provide a vision of the range of possibilities for the computer in education, forcing attention to the research issues needed to achieve those possibilities, and helping us to solve the problems involved in bringing new sources of learning power

into the nation's many and varied school systems.

These four general recommendations, for a coherent, continuing effort, for the development of prototype systems, for basic research, and for efforts relating to implementation and teacher training are discussed in the next four sections.

A COHERENT NATIONAL EFFORT

In order to be productive, the projects we propose should be integrated into coherent combinations of basic research, prototype development, and field implementation. The researchers who lay the foundations for improved uses of computers in the learning process must be involved in field testing so that research and practice can inform each other. Researcher interactions with teachers as they learn to use these new tools is especially important. We see prototype teacher training efforts as a partial responsibility of the researchers who are funded based on our other recommendations. At the very least, those researchers should be major consultants in the development of training systems, both to preserve the involvement of the knowledge producer in knowledge application and because of the feedback that teachers can provide, through this mechanism, to researchers.

Projects should be large enough in scope and duration to provide clear outcomes. None of the more exciting possibilities we have considered can be realized, even in prototype form sufficient for testing of efficacy, without multiyear efforts by cooperating, interdisciplinary groups of researchers, teachers, school administrators, and parents. The work need not be restricted to a single institution; indeed this may be a serious limitation. However, it should be concentrated in a small number of projects, each of which involves prototype development as well as basic research and/or school implementation efforts. This suggests an imaginative funding competition. Both large and smaller initial proposals might be solicited, after which existing multifaceted efforts that survive the competition might be funded directly while smaller-scaled proposals that are of high quality might be the basis for the negotiation of a multi-institution consortium.

DEVELOPMENT OF PROTOTYPE COMPUTER SYSTEMS

Intelligent computer systems can contribute to current efforts to increase the amount of reading and writing children do and the amount and quality of feedback and guidance they recieve. We recommend that several prototype systems be developed to exploit this possibility. One important need is to develop communication networks tying together classrooms, libraries, and other information sources and information processing tools on a local, regional, and perhaps national level. Some of these information sources and information processing tools are themselves targets for prototype resources that are likely to substantially improve literacy instruction and are unlikely to otherwise be developed and tested in any powerful form.

Information Resources

Electronic Libraries

We recommend that one or more prototype electronic libraries be developed. These libraries should be very large data bases of information that can serve as source material for student writing. Having substantial material available to students via computer network has several advantages. First, it provides a common information source that is rich enough to support a variety of writing tasks. Students can receive research assignments, criticize writing already in the database, synthesize different bodies of information, and perhaps even contribute information of their own. A second advantage of the electronic library is that teachers can receive training in precisely the same environment available to students. Methods tried out in practicum courses would not suddenly fail because they refer to books not in the local school library. Techniques that worked at one school could be published and used intact by other schools (indeed, we assume that electronic school library systems will eventually be used by teachers to exchange ideas about writing assignments that have worked well). Finally, the skills of data base access and information retrieval are themselves part of what will constitute literacy in the future, and students will best learn these skills in the context of substantive information needs.

Indeed, scholarship has always involved finding, understanding, analyzing and extending existing ideas. In that sense, what we are calling for is research on new resources for accessing and analyzing information, along with exploration of whether these new forms can be used to improve the scholarly abilities of our populace.

Automated Dictionaries

While the communications technologies make access to distant electronic libraries feasible, other technologies allow the possibility of mass-produced local information resources. We recommend that the microcomputer and videodisc technologies be used to produce intelligent, automated dictionaries and thesauri. With such systems, for example, the "circulatory system" could be explained by an animated visual presentation of blood circulating in an animal, together with explanatory text concerning the process. Definitions of words could be accessed while reading, through touching the screen, or while writing, by typing an approximate spelling.

This ease of access should make a qualitati ange in the way dictionaries are used. For example, there is some evidence that children who do not learn very well are less prone to attend to precise meaning and to details of a text. By decreasing the effort required to access information about terms used in texts, we may well create a situation in which slower learners learn that precision and completeness in reading a text will result in better learning.

Products which make existing forms of reference information (e.g., dictionaries) accessible to computer systems already exist. The research issues we raise are (a) are there new forms of intelligent reference systems that are worth producing, and (b) how can automated reference systems be used effectively in the schools. Given current research on vocabulary and its relationships to intelligence, it seems likely that more than definitional information will be needed, that automated dictionaries will need to be smart enough to teach differences in nuance between apparent synonyms, for example.

Interactive Text

Similar benefits may come from extending the automated dictionary concept even further, into the interactive text. The prototype we have in mind would include the kinds of explanatory resources just described, so students could ask to have a concept explained or a point elaborated. In addition, the interactive text could have questions embedded within it for students to answer. Some analysis of children's answers to those questions would be performed and subsequent presentations would be geared to the level of understanding revealed by those answers. Interactive texts of this type will make reading more like conversation with an expert.

Information Processing Resources

Coaches And Tutors

Artificial intelligence research has proceeded to the point at which a variety of coaching and tutoring activities can be conducted by a computer system. It is time to begin building prototype intelligent tutors so that we can study the efficacy of such approaches. A writing coach could aid students as they try to generate ideas and plan their writing. It could also help students think about their goals and encourage them to continue writing. When the student has finished a draft, intelligent text analysis tools could analyze it in terms of spelling, grammar, and style and make suggestions for revision. A computer coach might even prompt writers to read their text reflectively and to use good strategies in revising the text. In order to develop high quality writing coaches, we need research on the writing process in skilled writers and in students at different levels of achievement. On the other hand, the existence of preliminary systems will greatly enhance and better focus such research.

With videodiscs and microcomputers, it also becomes possible to provide students with models of skilled performance in many different tasks, such as skimming, studying, generating ideas, revising text, etc. That is, children could be given access to interactive texts that explain what a skilled reader or writer does in various situations. In order to develop tutoring systems for the various literacy skills, we will need to develop computer-based models of skilled performance anyway, since tutorial systems operate in part by comparing an analysis of what a student did to analyses of expert performance. Perhaps students can benefit from direct access to these models as well as from the tutoring systems that use them.

Communication Networks

We recommend funding of one or two computer network projects. These projects should test existing network tools, building prototypes of new ones as necessary. Computer networks can provide three different kinds of access to information sources: (a) access to information and tools not available in the classroom, (b) access by students to other students and adults with whom ideas and suggestions can be exchanged, and (c) access for teachers to share resources and ideas. For example, students might use a network to help them write about some topic, such as why the rainbow has different colors. To do this, they might send messages to their friends to ask for suggestions on what to read or advice on what tack to take in their writing. They might retrieve texts on rainbows through the network from an electronic library. Later they might send drafts of their text to friends for comments and suggestions. Such networks provide an environment where reading and writing arise in a natural context.

Networks, therefore, provide a powerful context for learning to read and write. They also provide resources beyond the physical constraints of the classroom, both for students and teachers. The cost of sending messages is quite low (even messages sent across the country cost only about 10 cents each). However, one reason for building prototype networks is to allow exploration of the relative economics of local and long-distance networks, to learn what costs attach to what sorts of uses, and to foster the development of schemes that realize the exciting possibilities of information networks for literacy instruction without the expense of free, unlimited telegraph service for all school children.

Good local area network projects need to be sponsored. These should provide exemplary prototypes of both hardware and software needed to support a closely-knit user community within a school or a geographically constrained user community.

Networks, Videotex facilities, data banks for parents and children, and computer-based bulletin boards are already starting to be developed. However, there is need for further support in this area, with attention given to richer analyses of usage, analyses that include observational work, cognitive performance (task) analyses, and more traditional achievement measurements.

BASIC RESEARCH IN COGNITIVE AND SOCIAL PROCESSES

If we are to realize the potential of computer technology for helping students develop as readers and writers, we need research of several kinds. First, we need to understand what motivates students to become active readers and writers, and we need to understand how computers can be used to support these interests and not limit them. We must also understand how computers can provide readers with resources ranging from advice while reading and writing to convenient library access. We need certain types of computer science research that explores the uses of computer technology in diagnosing individual student's difficulties with reading and writing, and the uses of computers in helping students overcome problems. Finally, we must remain alert to the effects, both desirable and undesirable, that various uses of computers may have on students' patterns of development as readers and writers and on the social organization of the classroom.

We have several general recommendations for how research funding should proceed. One view of this research agenda encompasses all of cognitive and developmental psychology and much of computer science. The advances of the past two decades in cognitive psychology, linguistics, artificial intelligence, and cognitive development are the basis for the exciting possibilities for computers in education that motivate this report. We support long-range national investment into these research areas but limit our recommendations here to domains of research from which we expect a shorter-term payoff: enhanced design principles for interactive instruction and information retrieval systems for education. There are multiple environments and strategies for carrying out this research. Some of it could be done in relatively isolated laboratories; some should be carried out in the context of developing prototype systems; some will be enhanced by large, multi-disciplinary research and design teams. In every case, we strongly urge that the research integrate the insights of teachers and other education practitioners with those of scientists. The development of useful systems will rest on the twin pillars of practical and theoretical knowledge.

Knowledge Retrieval

The basic research agenda in this area can be divided into three parts. We need greater knowledge about: (a) How humans (young and old) store, process and retrieve information already contained in their heads and how they can improve the efficiency and effectiveness of these processes. (b) How humans (young and old) acquire new information from their environment--especially computer assisted environments--and how to improve this acquisition process. (c) How information sources (documents and computer files, electronic and traditional libraries, printed and electronic dictionaries) can be designed to facilitate information acquisition by humans. Without the better answers to these questions, our design strategies for effective computer-human interaction and retrieval systems will be primitive at best.

Retrieval And Use Of Prior Information

Research should be funded that addresses fundamental issues in human long-term memory storage, organization and retrieval. It should address such questions as the following:

(a) How well do students understand the degree of knowledge they have about a particular subject? What prompts them to search for additional information?

(b) To what degree must a person and a machine have the same organization of information in their memories in order for one to retrieve information from the other?

(c) How can we produce or provide clues to students so they can remember more, organize prior information more cogently, and acquire information from other sources more efficiently?

(d) Under what situations (if any) do students overestimate their knowledge or believe false knowledge? Can this be identified and remediated?

(e) How do the cognitive skills needed for effective memory storage and retrieval develop? Should we structure information-rich environments differently for different-age children?

(f) To what extent do cultural and social experiences influence memory storage and retrieval processes? What effect should this have on the design of computer-human interaction systems?

(g) What are the heuristic strategies of persons (young and old) who are skilled memory retrievers? Can these strategies be taught to others?

Acquiring New Information

We recommend that some research funds be allocated for studies in the psychology of human learning, information processing, and systems design. Specifically, research is needed on methods for improving student-computer interaction (for all ages of students), and on modeling what a student knows in order to tailor presentations to his/her needs. The development of models of skilled reading of familiar and unfamiliar text is another especially important task in this area. Other research questions that bear directly on the design and use of intelligent systems include:

(a) What are effective human retrieval strategies (heuristics) for familiar and unfamiliar rich data bases? What do we lose or gain by automating retrieval systems to as high a degree as possible?

(b) Are there differences in effectiveness between "bottom-up" (inductive) and "top-down" (deductive) retrieval strategies? Are these differences general, or do people differ in which strategies suit them best?

(c) To what degree should the nature and complexity of computer referencing and retrieval systems vary for students of different ages or backgrounds?

(d) How can students be prompted to make intuitive or anticipatory leaps in the acquisition and comprehension of new information?

(e) What are the best mixtures of teacher and machine assistance in the acquisition of new information?

Refining Information Sources

The Department of Education has already sponsored a successful project on document design. Results from that work will be of great utility in designing effective information systems for schools. However, there is need for more specialized research that relates specifically to the possibility of delivering information via intelligent machines. The questions listed below illustrate the kind of additional research that is important.

(a) Are different media (e.g., sound, text, pictures) necessary for effectively transmitting different kinds of information to students of different backgrounds (age, prior knowledge, culture) for different purposes?

(b) How do we best integrate text with sound and pictures (particularly animations and films) for effective imparting of information?

(c) What kinds of cues, probes, and strategies can an effective retrieval system use to make the human task easier?

(d) How can interactive texts be designed to facilitate access to relevant information at a level appropriate to the reader's skill and knowledge level?

(e) How can the comprehensibility of text best be evaluated?

Comprehension And Writing Strategies

Research to date suggests that even secondary-school students have difficulty summarizing texts, defining main points, skimming text to abstract information quickly, taking notes, and planning and revising compositions. So far, most research has focused on sentence-level reading and writing activity, analyzing skills that are either spontaneously available or readily taught. Higher level (whole text) activities such as summarization and planning are clearly of equal importance, but are not yet as well understood. We envision computer aids that will help students by controlling which information is presented and how it is paced, by highlighting portions of the text, etc. However, we need greater understanding of higher-level literacy processes before we will know which possibilities are likely to pay off.

Self-monitoring And Intentional Control Of Text

Even after we identify the strategies most effective for various reading and writing tasks, we still face the problem of discovering effective ways to teach those strategies. We also need to assure that the automated tools that we provide for students do not become barriers to better human skills. Four strands of research are proposed with the intention of creating the research base needed to promote the design of effective computer programs for assisting, prompting, and teaching effective comprehension and writing skills.

(a) Theories of internalization of control. When the computer acts as a mentor, its reasoning should be transparent to the student so that the computer's strategies will be internalized by the student. We need to know how such prompts become internalized so that we can insure that their use will not encourage passive strategies.

(b) Parameters for effective use of computer-based procedural facilitations. We need to know when (and for how long) students should be actively coached through reading and writing tasks. We also need to know which mentor functions are best carried out in the social milieu of the classroom and which in the more private space of the computer terminal.

(c) Role of prior knowledge in effective use of mentor functions of computers. The successful use of coaching techniques will also depend on the materials and context in which they are applied. We need to know more about these factors, to determine the conditions of prior knowledge most conducive to internalization of control procedures and the conditions that will best foster learning of new content in diverse subject areas.

(d) Training attention to cues useful in guiding writing or reading processes. Difficulties in reading and writing are sometimes caused by failure to notice the cues that an expert would use to control reading and writing processes. For example, children may write sentences which lack parallelism or paragraphs which are poorly organized because they fail to notice lack of parallelism or poor organization in the text they generate. Unskilled readers may not take a sense of confusion in reading a text as a cue to reread or to search the text for the answers to critical questions. Research is needed to develop techniques for teaching students to notice and respond to symptoms of inadequate understanding or inadequate communication of ideas.

Diagnosis And Intervention

Teachers have difficulty in identifying students' literacy problems quickly in their busy classrooms. They could benefit from interactive computer systems which make (or help to make) diagnoses of student skill levels. For example, a diagnostic package which probed the students' ability to detect problems in grammar and organization or to identify major points in a text could alert the teacher early in the semester to special needs of students for remediation. As the complexity of diagnostic assessment increases, new psychometric models based on cognitive theories of competence in reading and writing should be developed. These models may be used in guiding decisions about how optimally to sequence diagnostic tests of reading and writing should be developed. These models may be used in guiding decisions about how optimally to sequence diagnostic tests of reading and writing skill. They will also help us summarize and interpret complicated patterns of errors in students' performance on criterion reading and writing tasks. Further, they will permit us to study and summarize changes in student's diagnostic profiles over time.

As we discover powerful ways to diagnose students' reading and writing abilities and difficulties it will become possible to combine diagnostic assessment with coaching and tutoring of enhanced literacy skills. For example, in writing it would be possible to summarize strengths and weaknesses of writers in such areas as punctuation, grammar, diction, rhetorical organization, and suitability of writing style for a given genre. In addition, it might be possible to assess strengths and weaknesses in editing and revision. Within each of these areas it then would be possible to tailor training in writing skills according to the kinds of problems encountered in each area.

Diagnostic assessment and training of literacy skills by interactive computers may become an extremely important vehicle for overcoming the educational difficulties of students from special populations; students who are handicapped or who suffer from learning disabilities have special educational needs which might be better met with computers. The same can be said for students from non-English backgrounds or students from backgrounds where English literacy training has not been extensive.

It is essential, as computerized intervention systems are developed, that they be evaluated carefully. At least four questions must be asked of such systems: (a) Do they have any positive effects at all? (b) If so, how long do these effects endure? (c) Are the positive effects transferable to everyday academic language use and problem solving? and (d) Do the effects replicate over different student populations, materials and environments?

Motivation

While solid research has yet to be conducted on this issue, we suspect that students' use of computers in classrooms may affect their motivation to learn in both desirable and undesirable ways. The availability of powerful computing resources to help students acquire reading and writing skills may enhance development of a personal sense of literacy, leading the student to participate more fully and effectively in everyday classroom activities. For example, availability of electronic mail systems and use of computers to create classroom newspapers may increase students' interest in using literate media as a means for communicating ideas. This increased motivation to read and write may have positive long term consequences for learning how to learn, developing idea generation skills, and developing social skills. One can also imagine negative motivational consequences arising from misuse of computerized tools in the classroom. Excessive interest in computerized learning games as a means of entertainment may lead students to lose interest in participating in teacher-led activities or sustained independent work. Students who are already poorly accommodated to the social life of classrooms may become even more poorly adjusted. This may occur because students become more withdrawn as they interact less with other students and teachers and more with computers. Some students may also lose self-esteem because they find that they are not as skilled in computer activities as other children. We recommend research dealing with issues such as the following:

(a) What are the motivational consequences of instruction by computer, teacher-led instruction, student group activities, and individual seatwork? Which approaches should be used when?

(b) Computer literacy stands a chance of creating yet another area where differences between the least able and most able performers create new social class divisions. If less able students use computers primarily for diagnostic and remediation purposes while more able students are engaged in more creative activities, will only the latter come to regard the computer as a powerful tool rather than a taskmaster?

(c) While computers can create motivating game environments, we do not want to make students addicts of artificial reinforcement. There is another potential problem. Ideally, in using a tool to solve a problem, the user's attention should be on the problem and not on the tools. Adding motivational features to a computer tool may focus too much attention to the tool itself. Research addressing these problems should be encouraged.

(d) How can computers be used to improve self-perception, social interaction skills, and pride in computer literacy as a personal form of expression?

HELPING SCHOOLS BECOME COMMUNITIES OF EDUCATIONAL COMPUTER USERS

Even the best tools for computer-based education will not be widely used unless (a) care is taken to put them in forms that solve school systems' problems; and (b) effort is allocated to teaching teachers how to use these resources. In this section, we present first a set of goals and concerns that we feel should pervade all national efforts to improve computer-based education. This is followed by a set of recommended activities related to development and implementation of systems that can significantly improve education.

Goals And Needs

Computer as Helper, not Master. The computer can be our servant in education, a new kind of servant that can be asked to do things we have never before tried to do ourselves. We must be trained in order to best be served by it. In our vision of new possibilities, we must also recognize the limitations of our computer helper. A computer cannot replace human role models in education, nor is it smart enough to supplant human teachers in their sympathetic interaction with children. Our national goal for the computer in education should be to find ways for it to help children learn, help eliminate teacher tedium, and give the teacher effective support systems beyond the capacity of parents, local schools, and school districts.

Challenge of New Technology in a Democracy. Some people fear that the computer will increase the already wide gap between the haves and have-nots, between those who use computers routinely in their homes, and those who cannot afford such luxuries. The danger of ignoring the special needs of the educationally disadvantaged should be recognized, and policy should ensure that this does not happen. If this tool is to be made available to our schools, it should be made available to all children equally. A unique opportunity of the new technology for education is to extend the learning environment beyond the school and into homes. Yet, special care must be taken to avoid intrusion on parents' rights and responsibilities and to assure that equality of computer-related opportunities in the school is not eroded by differences in home computer availability.

The traditional Jeffersonian aim of a universally literate democracy should be extended to include computer literacy and math and science literacies, as well as literacy in reading and writing. The computer can support this traditional democratic ideal by its flexibility in filling the needs of special students, including the highly talented, the handicapped, and the disadvantaged. Its potential as a tutor for special students should leave the teacher free to teach in more individualized and imaginative ways. In all this, the computer should remain an optional, not a compulsory tool. Its use should be left to local wisdom and judgment.

Need for Training. Our experience with the introduction of educational television suggests that schools and school districts must plan for staff training if new technologies are to be fruitful in the classroom. If we do not assist our underpaid teachers in the task of learning about computers in the classroom, the enterprise will fail. Teachers as well as students and parents need our help both in advice and training, and we also need to engineer the classroom computer tools we build so they are understandable and usable by a wide range of people. Electronic technology is no longer the domain solely of engineers and scientists. Computers are for everyone. Professional development resources relating to computers in education must be extended not only to the math and science teachers but also to teachers of reading, writing, and other skills we expect in our citizens.

General Policy Recommendations

Research On Computer Potentials

The U.S. Department of Education should support innovative and far-reaching research designed to analyze the potential of computers for improving education in order to help policy makers, educators, publishers, and manufacturers anticipate the consequences of introducing computers on a broad scale into education. It is important to anticipate the changes computers are bringing before the effects of these changes are widespread.

Analyses should include research on new roles for teachers, new organizations for classrooms, and new educational settings. For instance, analyses should be concerned with the following roles: (a) the role of the teacher as selector of existing courseware, as courseware developer, classroom manager, coordinator of "intellectual communities" established through computer networks, and as creative tutor and coach; (b) the role of the student in peer tutoring, network "community" member, database user, courseware developer, author, and editor; and (c) the role of the administrator as the person responsible for learning resources and computer courseware development centers, as a teacher training specialist, as network library coordinator, and as research and development liaison coordinator.

Other innovations should include research on new organizations of students beyond and within the classroom that may result (or be worth trying) when powerful computers are introduced into education. Furthermore, careful consideration should be given to new definitions of curriculum, of instructional research and development, and relations between the school and community. Our perception of community may change, too, as computer networks increasingly extend across regional and national boundaries. We should explore the potential of such international exchanges.

The use of computers in schools raises a number of economic issues. Research should be undertaken to analyze the cost and benefits of alternative forms of hardware and software, of retraining, and of authoring systems and other instructional software programs. Financing computer use in the schools, and the benefits of cooperative development of software, should be reviewed. Another research focus should concern the economic impact of computers on labor intensive school organizations.

Quality Assurance

The software initially sold to school systems was mostly of mediocre quality or worse. A variety of initiatives will be required if this situation is to improve to the point where we can think of computers in the schools as a major factor in fostering excellence in education. Efforts should be made to integrate practitioners, scholars, technical experts, and other appropriate persons, into the computer systems development process. This will require such research as the following:

(a) Observational research on the use of computers in various educational settings, looking for constraints or barriers to implementation, and possible ways to overcome those barriers and constraints.

(b) Efforts to establish university-school-publisher collaborations to design, develop, implement, and evaluate software.

(c) Greater concern for educational applications in such basic computer research as the study of human-machine interactions and the ergonomics of hardware designs.

(d) Research on systems for field testing and evaluating all courseware, not just prototypes. Quality guidelines should be established for authoring systems, for instruction and assessment, for selecting software programs, for field testing and evaluating in school settings, and for developing software in the private sector.

(e) The development of an automated data base of information on computer tools for education, common languages for authoring, and demonstration collections of courseware materials.

Training Prototypes

Teachers of reading, writing, language arts and English need continuing education. In addition to subject-matter revitalization, as can be by such resources as the National Writing Workshops, there will need to be opportunities for teachers to become familiar with computer resources and to learn how to use them well. Excellence in the technology-driven education world we are entering will require the development and evaluation of innovative prototypes for training present and future school personnel. Possible sources of such training include research and development centers, labs, summer institutes, teacher-training institutions, and the schools themselves. Obviously, some of this training might itself be delivered by computer. Teachers being trained should be provided with on-site use of computers for experimentation, and provision should be made for text materials, demonstrations, teacher models, practice opportunities with feedback from the teacher trainer, follow-up monitoring, and other support services. It is important that training efforts be based on the best instructional research, and that they undergo field testing, to ensure high quality.

Long Term Evaluation

We also recommend long-term on-going evaluation of computer uses in schools to assess the effects of individualized computer-based instruction on the achievement and self-concept of students. Studies should be conducted to compare computer-based instruction to alternative approaches. Other assessments should review the effects of hardware and software on such student variables as achievement, time-on-task, self-concept, and attendance and on such teacher variables as effectiveness and burnout. A broad study of the impact of computer and video technologies on children's development should be considered.

Specific Funding Recommendations

Our specific recommendations for development and implementation research fall into the following four areas:

(a) The classroom as a community. We need to assure that computers do not destroy valued aspects of classroom instruction and to foster the effective use of computers in classrooms.

(b) Professional support for teachers. We need to avoid both the actuality and the perception that the computer is being used to further subjugate teachers or to deprofessionalize their role. This suggests that effort should be directed toward prototype systems that can save teachers' time and free them for professional development, better lesson planning, and more one-to-one interactions with individual children that can improve the excellence of American education.

(c) Computers in the broader community. We recommend research on networks to interconnect classrooms and other places where learning happens, such as the home; arrangements for the involvement and training of teachers and parents; and the possibilities for better articulation of learning at home with learning at school in an information-rich world.

(d) Computer literacy. We need to teach our fellow citizens about computers. A number of the recommendations made to deal with other concerns will help solve the problem of teaching parents, teachers, and students what computers can do, how they work, how to use them, and the general skills of problem solving that are needed to use them with facility.

The Classroom

The classroom has evolved over the years as our primary mode of instruction for school children. Adding computers to the classroom must be done in ways that do not destroy the good already present. This suggests that there must be careful analysis of the patterns of interaction in non-computerized classes as well as those to which computers become available. Further, there is need to provide advice to schools on the kinds of classroom arrangements that work best when computers are used.

Currently, social interactions between students in class tend to be limited. Very little of the school day is spent in serious team efforts, even though we rely heavily on our schools to teach children how to work together to solve problems. Computers can help or hinder peer interactions. In the worst case, they will reduce learning to an even more solo activity. In the best case, they can create the possibility for significant peer interactions in the solving of problems and the development of understanding.

Prototype school and classroom designs. Research should be supported that leads to well-motivated prototype designs for computerized learning facilities: computers in classrooms, combinations of in-school and out-of-school facilities, and, if it should prove effective, resource center arrangements. Demonstration sites that can be evaluated will be necessary. Such sites should emphasize joint involvement of students, teachers, and parents in the learning process. Again, they should address the issue of when computer-based activities are effective, not just whether they are. Prototypes that assure students free and rich access to the computer throughout the day are especially important.

Making students more able to learn. It is important to create systems for students that allow (and help) them to make their own reading and writing tools. A general purpose computer language that is specially adapted to language (in the way the LOGO "turtle" facility is adapted to geometry) could be used by students to develop their own reading and especially writing tools. For example, a computer language based on topic-comment linguistic analysis could have procedures to amplify operating primitives such as "genre," "tense," audience," "man," "sad" into personally stylized text structures that communicate effectively and forcefully. The goal we propose is a prototype computer environment which emphasizes peer interaction in such activities as planning of compositions, classroom newspapers, and group business enterprises simulated on the computer.

Human engineering of computer systems for special students and for group activities. Display devices and input facilities for group use of computers should be encouraged. We expect such resources to be developed for business use by private enterprise and hope that as this happens, they will be deployed in some of the proposed exemplary prototype R&D activities. Special populations, such as the deaf or blind, should have specially adapted tools that help them read and write effectively. Appropriate computer use of visual or auditory natural language interaction is possible now and can be made available to this population.

Teaching Teachers And Administrators

One important way to assure that teachers invest the efforts that will be required for them to become facile computer users is to assure that some of the innovative development efforts are aimed at saving teacher time. As discussed above, teachers need more time if they are to achieve excellence in their efforts: for continuing education, for lesson planning, and for individual efforts with students. Each of the multiple roles of the teacher begs for technological support and transformation. Many roles require tools similar to those suggested for the learner, including assists for information creation, modification, transmission, location, and access. Besides these, other roles, specific to the teacher, could include (a) systems to teach teachers how to use specific courseware products; (b) systems to demonstrate to teachers the possibilities of sophisticated learning interaction formats, such as simulation, Socratic dialogue, intelligent prompt fading, or gaming; (c) systems for authoring or customizing instructional software; and (d) systems to support feedback and grading functions.

Feedback, grading and other teacher aids. Prototype software should be developed for the annotation of student writing assignments by teachers. Effective use of pointer devices such as the mouse and of menu displays would allow teachers to build libraries of standard comments that could be mapped onto a student's essay by pointing in turn to a location in the essay and a comment on a feedback menu. In addition, grammar correction and text summarization systems would help save teacher time. Prototype network systems that are developed for schools should include devices for enhancing teacher productivity, such as on-line homework assignment listings, lesson planning aids, and "blackboard note" recording systems. Loudspeaker announcements might be replaced in many cases with computer mail, if the systems are appropriately designed.

Software authoring and customizing systems. No national agency, whether government or publisher, can decide what is best for all students in all schools. Therefore, it is essential that teachers be able to modify instructional software systems to suit the needs of their students and the community they serve. One step toward this end is the development of software authoring languages that teachers can use to adapt software to their specific needs. A project should be launched to research and develop an instructional authoring system that would be based on a theory of instruction.

Such a system should define instructional operations, such as presentation of information, menu choices, or student assessment in terms of software so that programming these tasks would be relatively simple. It should provide for appropriate implementations of language subsets to permit authoring systems to be used on machines of limited capacity and by both instructional designers and classroom teachers. It should also facilitate movement of courseware from one system to another, by creating virtual instructional machines (for example, all courseware could reference a virtual screen of infinite resolution, which could then be mapped onto the screen for any particular machine; the North American Presentation Level Protocol Standard is a good example of this approach). Such a system should be a rich environment full of the tools designers and developers need to produce good instruction, including programs to support task analysis, student response, parsing mechanisms, and graphic editors.

A courseware development center. Courseware utility increases with efficacy--indeed, utility and efficacy may be the same. Efficacy is a function of such things as the appropriateness of the design of instructional messages, graphic layout, and learner-computer interactions. These features should be identified and information about them disseminated to developers and, perhaps, embedded in authoring systems.

The scope of authoring systems can vary enormously. On the one hand, systems can be adapted for machines no more powerful than can be found in classrooms with standard peripherals. On the other hand, it is possible to create a computationally rich environment, specifically for creating courseware, that fully exploits the audio-visual and instructional capabilities of classroom computers. Such a rich development center needs to provide full opportunity for dedicated teams of talented experts, in a wide array of domains, to apply their creative talents together to produce courseware of high quality. These production teams need the skills of teachers, subject matter experts, visual designers, graphic artists, creative writers, computer graphics people, and other experts.

Telling teachers and lay people about uses for the computer in education. Teachers and parents need to know what kinds of effective uses of computers are currently possible. At one level, this could be seen as a science reporting problem, but it is more than that. It is quite uncommon for fundamental research to lead to successful innovation in real applications without preserving the involvement of the basic researcher in the development process. Most information dissemination systems which attempt to bring new knowledge to the practitioner fail unless they involve the knowledge producer. Thus, we see the need for information dissemination that involves every project envisioned under these recommendations.

The contractor meetings of the Office of Naval Research are a good model for a part of this process. In those informal meetings, representatives of the applied research and development groups in the military services interact with basic researchers and share problems and ideas. The process is facilitated by the principle that the informal interaction, and not a formal document, is the goal of the meeting.

In addition to such informal interactions, though, a research center or a larger research contractor involved in other projects we have proposed should have the additional charge of producing information on computer usage for the schools that is understandable and applicable by teachers and parents. Such informational products should include reports of research results and their implications for excellence in education, critical guides to available computer resources, and models of effective computer deployments and usage at different levels of computer power, such as one machine per student, one per classroom, a few for an entire school, and combinations of home and school availability. Reports should incorporate successful activities generated at the local level and perhaps include analyses of why those innovations were successful and how they can be replicated.

We recommend evaluating alternative methods for wide dissemination of information about instructional, management, and other applications of computers in schools. Computer networks are an unparalleled resource for rapid dissemination of information. Alternative methods to be evaluated should include regional resource centers for the support of teachers and program developers in local school systems.

Tools for administrators. Administrative activities range from the classroom through the school to the school district. For each, administrative efficiencies can be greatly improved with the application of organizational computer tools. Simulation and modeling have proven their worth with expert systems devoted to analyzing throughput in factories. Similar tools, based on AI expert systems, for allocating scarce software, hardware, people, student, and building resources in educational administration at all levels could easily prove their worth and make more efficient use of scarce tax dollars.

A Community Of Learning Beyond The Classroom

Part of the work of learning, even school learning, is done outside of school. Students are given homework for a variety of reasons. It offers a chance to reflect on problems outside the regimented time schedule of the fifty-minute hour. It provides the additional practice that can be done largely without teacher assistance (or at least is not the highest priority use of teacher time). However, the home can be an incomplete environment for learning. There are usually fewer reference works. No one may be available with whom to discuss a problem. Even a phone conversation with a friend is difficult if the object of discussion is an essay the friend cannot see.

If the computer-based learning environment moves beyond the walls of the school, homework can change substantially. The resources of the classroom, if translated into machine-readable form, can be available outside the school. Groups of students can work together even if they live in different parts of town. The work of learning can occur at home as well as at school and in ways that go beyond homework as we currently know it.

If instructional computer networks are extended to places outside the school, such as the home and local libraries, then parents can be active participants in this extended learning process as well. However, a community of learners can only exist if its participants have become socialized in the ways of interaction. Parents need both specific traning in network information access, and, more generally, a chance to keep up with their children. Our society depends upon a respect for the wisdom of age that will be seriously eroded if the computer revolution leaves parents and teachers behind.

Exciting new possibilities occur when computers pervade home and school. A tool used in school may also be useful to parents. For example, we were told of a student who used the computer for interest rate problems one day and came back the next with specific problems his parents wanted solved so they could decide whether they could afford to buy a certain house. Prototype projects in this area may involve joint participation of researchers, a school system, and manufacturers.

However, these visions must be mediated by the realities of a world in which providing pencils to students is a burden some teachers meet out of pocket and in which the costs for home and school machines will compete with demands for teacher salary improvement and tax reductions. The value of a higher capital investment in computers for education must be demonstrated with care in visible, criticizable, assessable exemplary prototype projects.

Computer Literacy

We define two levels of computer literacy. At the minimal level the user can access and passively use already prepared programs. At the basic level, the computer user can actively work to modify and write materials of his/her own. We believe all children should achieve minimal competency and that many should achieve basic competency. However, we believe computer literacy is a by-product that cannot best be achieved by direct instruction. Children and other members of the community become computer literate by using computers to achieve other goals. Thus our primary recommendations for fostering computer literacy are already contained in other recommendations. For example, we proposed networks that would allow less able users to communicate with and learn from more able users, authoring languages that are easily used by teachers, students, and parents, and "autonomous" software that even inexperienced individuals can use freely and independently. These developments would aid all members of the community to become computer literate at the minimal or basic level. We do have the following two recommendations for sponsored research aimed directly at computer literacy.

A person trying to use a computer to do something often receives more immediate information about the success of his/her efforts than when using more traditional approaches. In this respect computer literacy is different from other subject matters. The writer of an essay or reader of a story does not know immediately whether it is successful or not. For this reason, unique forms of instruction may be useful in teaching computer literacy. For example, it is clear that children do teach each other to use computers. It may be that peer tutoring and individual exploration can have usefully expanded roles in this area. We recommend the development and extensive investigation of prototype instructional software and methods that show promise of being particularly effective and efficient in teaching computer literacy.

Computer literacy is particularly crucial for students in vocational, technical, and business courses. If computers are not used in these courses, students will emerge with incomplete and unmarketable skills, such as typing without word processing and diagnosing and repairing engines without computer tools. Guidance activities will inevitably be computerized, too. As we recommended earlier for English teachers, we recommend the development of prototypes for in-service workshops and autonomous instructional programs to increase guidance counselors' and vocational-technical teachers' knowledge of computers.

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