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ABSTRACT

The future of computers in education and the research needed to realize the computer's potential are discussed in this report, which presents a summary and the conclusions from an invitational conference involving 40 computer scientists, psychologists, educational researchers, teachers, school administrators, and parents. The summary stresses the basic conference conclusion 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. Details regarding this conclusion are presented for four topic areas, with an emphasis on the following research needs: (1) prototype research, including computer uses in coaching and tutoring, diagnosis, simulated laboratories, and games; (2) basic cognitive research, including research related to thought and learning processes, knowledge structure and knowledge retrieval, mental models, diagnosis of cognitive abilities, and artificial intelligence; (3) other research issues; and (4) implementation of research. (LMM)

Computers in Education:

Realizing the Potential

Chairmen's Report of a Research Conference

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COMPUTERS IN EDUCATION
REALIZING THE POTENTIAL

Chairmen's 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

June 1983

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Points of view or opinions expressed in this report are not necessarily those of the U.S. Department of Education.

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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 Indeed, surveys of computers in schools are outdated by the time they are published.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 parents represented. 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 socio-economic 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 document presents the conclusions of the conference, as reported by its chairmen. A second volume contains a more complete record of the proceedings of the conference, along with the papers that were presented and the committee reports.

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, are 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 groundbreaking 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.

Potential 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.

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

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

- *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 what 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 poorly 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 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 be 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 much 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.

An example of computer-based diagnosis 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 specific 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 database 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 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. 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.

Communications 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.

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 expecially 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 these 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 computers.

Research is needed on the motivational consequences of instruction by computer, teacher-led instruction, student group activities, and individual seat-work. 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 into the trap of motivating children to focus their attention on superficial reinforcers while playing "educational" games.

Research On The 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 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 prevade 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 know 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 center. 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 inevitible 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.

APPENDIX
CONFERENCE PROCEEDINGS

PART ONE: INVITED PAPERS

I. COMPUTERS AND EDUCATION

The Computer Age
HERBERT A. SIMON
Technologies for Learning
RAJ REDDY
Paradigms for Computer-based Education
ALAN M. LESGOLD

II. MATHEMATICS AND SCIENCE EDUCATION

Research on Science Education
JILL H. LARKIN
Research on Mathematics Education
ROBERT B. DAVIS
Teaching Mathematics
STEVE DAVIS
The Mathematics Curriculum K-12
HENRY O. POLLAK
Teaching Science
JIM MINSTRELL

III. READING AND WRITING EDUCATION

Research on Reading Education
RICHARD C. ANDERSON
Research on Writing Education
ROBERT GUNDLACH
Teaching Reading
CATHERINE COPELAND
Teaching Writing
BROOKE WORKMAN
Literacy
E.D. HIRSCH, JR.

PART TWO: REPORTS OF CONFERENCE COMMITTEES

I. Mathematics and Science
FREDERICK REIF, Chairman

II. Reading and Writing
ALAN M. LESGOLD, Chairman

Note: These papers, together with the present Chairmen's Report, are published in a separate volume *Computers in Education: Realizing the Potential, Volume II*, which is for sale from the Superintendent of Documents, U.S. Government Printing Office, Washington D.C. 20402.

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