Chapter 3

The Impact of Technology on Learning

Photo credit: Stevens Creek Elementary School, Cupertino, California

CONTENTS

Boxes

Figures

Table

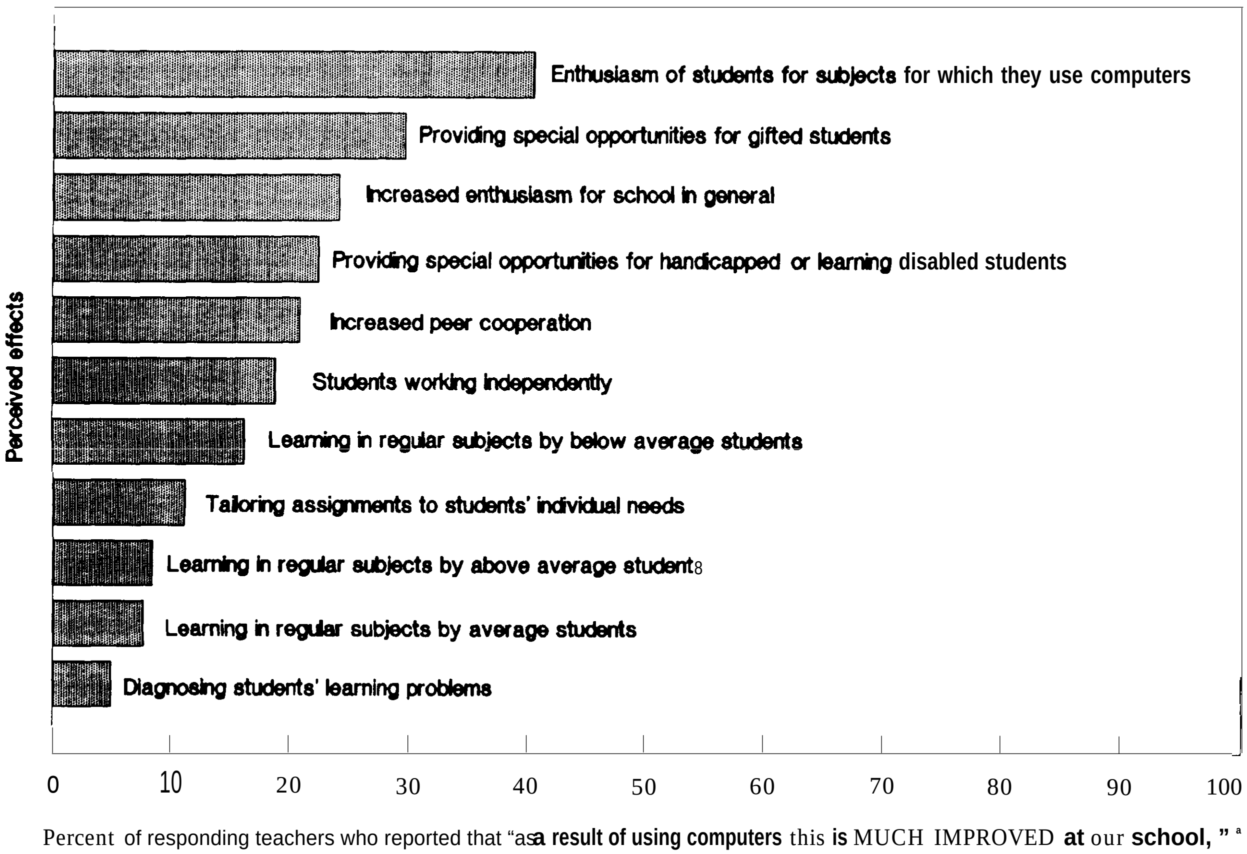
Chapter 3

The Impact of Technology on Learning

INTRODUCTION

One of the most obvious questions about using interactive technologies in schools is, "Do they work?" Against a background of growing concern with the way American public school children are prepared for productive adult lives, computers and other electronic media have been hailed for their potential role in achieving a wide range of educational objectives. While only a handful of the most fervent visionaries think that technology alone can solve the difficult problems of American public education, many educators believe that interactive technologies can be an important element, if not the linchpin, in a broader program of organizational and substantive reforms. Surveyed for their perceptions of the effects of computers in the classroom, computer-using teachers supplied a long list of educational objectives for which they believe the technology has a positive effect (see figure 3-1).

Figure 3-1.--Teachers' Perceptions of Effects of Using Computers in Classrooms



[a]Respondents could have chosen "somewhat improved," "little changed," Or "negatively affected."

SOURCE: 1985 National Survey of the Instructional Uses of School Computers, Center for the Social Organization of Schools, The Johns Hopkins University.

Given the promise of technology, a sizable number of educational researchers have taken an interest in systematic and scientific evaluation. State and local education officials also want to know about the performance of these technologies as substitutes and complements for alternative classroom strategies.[1]

The basic question—"Do they work?"–covers the full spectrum of our expectations (and demands) of the schools: Do the technologies improve students' acquisition of basic language and computational skills? To what extent are children's higher order intellectual skills sharpened or dulled by exposure to computer-related systems? Are traditionally deprived children–those with physical, emotional, economic, or geographic disadvantages—reached more effectively by electronic learning tools than by traditional methods? Do the technologies help or hinder children's socialization skills and motivation?

By and large, the research to date supports the continued use of instructional technologies in the schools. But it is important to point out that questions of performance and productivity are much more easily asked than answered, in part because the near-term effects of educational technologies are not necessarily the same as the vision of what these technologies might achieve in the long run. For example, there is evidence that computer-assisted instruction (CAI) can raise achievement test scores for some students; but there is also wide agreement that computer technologies can already do more than provide electronic equivalents of drill and practice workbooks, and that much of their future promise lies in experimentation and development of nontraditional learning methods.

Without evidence of short-run gains, teachers and students will lose faith in the long-run possibilities of the new learning tools; if so, it will be difficult to garner the political and financial support necessary to realize the technologies' potential. On the other hand, if short-run effects are overemphasized, researchers and practitioners may lose sight of the longer-term potential, in which case the grander vision of the technologies' role in education will remain a vision.

This basic tension is manifest in much of the literature surveyed in this chapter. Many early studies of CAI, for example, relied on changes in standardized mathematics and reading scores as the criteria for effectiveness. This approach allows for rigorous measurement, because test scores provide a quantitative proxy for a range of cognitive outcomes; but there is concern with the validity of standardized tests generally, and with their impact on teachers' classroom strategies. Further, standardized tests are not indicators of long-run effects of interactive technologies on higher order analytical and language skills specifically. On the other hand, tests that could measure other goals of education, including motivation, creativity, and social behavior, are necessarily constrained by state-of-the-art measurement techniques.

The research reviewed here addresses a wide range of learning technologies, applied in many different settings with diverse populations of children and teachers. Although the results are somewhat scattered and impressionistic, they do suggest how certain configurations of hardware and software, used with particular populations of children and under the supervision of competent teachers, contribute to the achievement of specific instructional objectives. In the light of these considerations, **school administrators planning the implementation of a particular computer-based system need to tailor the application to their school's and students' needs,** and should not expect to see aggregate research results exactly replicated in their particular environment.

[1] The issue of cost-effectiveness, i.e., how the technologies compare to other methods per dollar of expenditure, is taken up in ch. 4.

FINDINGS

- CAI has been the most researched of the various interactive technologies. It has been demonstrated to be an effective supplement to traditional classroom instruction. In particular, elementary school children who used CAI showed gains equivalent to between 1 and 8 months of instruction over peers who received only traditional instruction. CAI may be more effective for low-

Photo credit: Kjell-Jon Rye, Bellevue High School, *Bellevue, Washington*

Hands-on technology applications provide meaningful contexts for learning and encourage students to learn from one another.

achieving students than for average and high ability students, even when controlling for base-rate differences between these groups. While most conventional CAI programs involve drill and practice, there is evidence that the method can be applied to improving higher-order thinking skills among disadvantaged children. A number of CAI studies have been challenged on methodological grounds.

- Intelligent CAI (ICAI), or intelligent tutoring systems, represent an attempt to apply advanced artificial intelligence techniques and theories of human cognition, and are considerably more complex than standard CAI. ICAI programs employ a wider variety of teaching strategies than conventional CAI, and allow for more thorough analysis of individual students' skills, knowledge, and problem solving processes. Some ICAI systems track an individual user's thought processes, identify problems, and provide specific exercises in response. Experimenters with ICAI have pioneered new approaches to teaching of mathematics, science, and language. These technologies, especially those that are based on so-called "natural language processing, " are still in their earliest stage of development.

- Effects of teaching computer programming *as a* means to learn analytical skills more generally are mixed. The possibility of using programming as a way to prepare mathematics teachers has gained credibility, although new and better research is needed. There is limited evidence that programming develops basic thinking abilities.

- Simulation programs have been effective in teaching principles in both the physical and social sciences.
- Microcomputer-based laboratories (MBLs)--probes and measurement tools attached to a computer for use in scientific, mathematical, or musical laboratories–have been shown to help students grasp complex concepts as well as to master important analytical techniques (like graphing). The skill of the teacher using the MBL is a critical factor.
- The teaching of graphing concepts stands out as an exemplary application of computer technology in the classroom.
- Database management programs have become very popular in classrooms. Limited research results suggest that students who use computerized data management systems outperform other students in tests of information processing skills, including identification of requisite information to solve a given problem and selection of efficient modes of organizing information.
- Word processing tools account for roughly 10 percent of the available instructional applications of computer technologies. While these tools do not, in and of themselves, create better writers, they have demonstrated their importance in easing the physical requirements of writing and revising. Both normal and learning disabled students who used the word processor as a supplement to writing instruction made significant gains in writing ability, compared to control groups that did not receive the computer-assisted intervention. In addition, the advent of word processing technology has stimulated new research on essential strategies for reading, critiquing, and revising one's own written work, some of which are now being incorporated into new writing software.
- Reading comprehension can be strengthened through computer-aided reading programs that aim to improve comprehension through interaction with the whole text. These include decoding and word recognition programs, text mediation programs, and speech synthesis. Disabled readers seem to enjoy using these technologies, and have made progress in important aspects of reading.
- Electronic networks—local, national, and international—build cultural bridges that connect children working on different types of projects in different places. Several science-related communications networks are particularly promising. In addition, these systems offer a form of "distance learning" to children and teachers in remote rural areas.

EVALUATION RESEARCH: **SCOPE AND METHODS**[2]

Most of the data on the effectiveness of educational technology comes from research on the uses of computers to enhance learning. The computer has several unique features relevant to education. The computer interacts: students provide information to the computer and receive immediate feedback. The computer is precise: learners must be specific and precise in their instructions or responses. The computer is consistent: instruction and feedback provided in a computer program will be the same for every student who interacts with that program. In addition, the feedback a student receives is private. Children do not risk public criticism and embarrassment with a response, and they often have many chances to try again. The computer can provide multiple and dynamic representations of a concept, phenomenon, or a relationship.

Over the past 30 years, computers have been used in education primarily to provide drill and practice or to convey traditional course content. These uses of the computer had the benefits of releasing teachers from the drudgery of drill and practice, freeing them to work with other students on more complex material, and motivating students to attend to otherwise tedious learning tasks. These early uses of the computer did not necessarily address the more creative, reflective, or meaningful aspects of learning.

[2]The remainder of this chapter draws heavily on Joanne Capper, Center for Research Into Practice, "Computers and Learning: Do They Work? A Review of Research," OTA contractor report, Jan. 21, 1988.

It is only in the last few years that computer use has moved beyond this workbook approach to learning. Only now are there more than a few software and computer applications that encourage the active construction of knowledge, provide meaningful contexts for learning, promote reflection, foster intellectual work similar to that encountered in an adult's work world, and free students from many of the tedious aspects of learning,

There are several approaches to studying the effects of computers in the classroom.[3] Cognitive researchers focus on the intellectual processes that are tapped by the computer. Their focus is often the individual student engaged in a problem solving task. Because research in cognition has successfully explored the finer-grained aspects of teaching and learning, it has been able to contribute to some of the more sophisticated developmental work with computers. The strength of this line of research is that it can tell us how something works (e.g., a piece of software) and why it affects learners that way—valuable information to guide future efforts.

Other studies consider how the technology or the software is used by individuals, by small groups of students, or by entire classrooms. Often the intent of this type of research is to improve the software or computer application, or to determine the extent and type of training needed to support teachers in their use of the technology. Some studies of this sort explore the contextual factors that influence how computers are used in schools—factors such as district support, extent of resources (hardware, software, and training), or equity issues. Traditional experimental studies where computer-using students are compared to control groups of students working on the same topics without computers can reveal whether or not a treatment worked in a particular setting; but they usually omit information about why a particular treatment worked.

Current testing techniques are relatively advanced in assessing whether or not students have learned basic content knowledge, but are still immature in assessing more complex thinking skills and changes in attitude toward learning. Many computer applications aim to enhance complex types of thinking and problem solving abilities. Without appropriate techniques to measure these abilities, we can only infer effects. Consequently, the research findings reviewed in the following pages are limited to effects that can be currently measured.

[3] The review of research that follows is intended to be Illustrative rather than comprehensive. The studies described were selected to give the reader a sense of the type of research underway and the trends that are emerging from the results of that research.

The methods used for identifying sources consisted of: 1) Educational Resources Information Center (ERIC) and library searches; 2) references cited in research articles; 3) telephone calls to funding agencies (U.S. Department of Education, the National Science Foundation, and the Office of Naval Research); and 4) telephone calls to researchers regarding the status of their work and to identify others working in the field. The latter two methods were found to be the most efficient in that funders and researchers tend to be familiar with the work of their colleagues.

The primary focus of this review is computer-tool applications as used in basic subject areas. The areas not addressed include: computer use at the college and university level; computer use in military training; Instructional design issues social, affective, and equity issues video discs; distance learning modeling; and computer applications in art, music, foreign language, or vocational education.

COMPUTER-ASSISTED INSTRUCTION

For almost 30 years, computers have been used to provide instruction and drill and practice in basic computation and language skills. CAI is the oldest instructional application of computers and the most researched.[4] The early CAI programs were provialed through large mainframe, time-sharing computer systems, operated and controlled from a central location. Examples of such systems include PLATO (Programmed Logic for Automatic Teaching Operations), created at the University of Illinois, and Stanford University's CAI project for elementary reading and mathematics skills.

[4] See, for example, P.K Burns and W.C. Bozeman, "Computer-Assisted Instruction and Mathematics Achievement: Is There a Relationship?" *Educational Technology* October 1981; Joanne Capper and Carol Copple "Computers in Education: Research Review and Instructiona Implications, " *The Research Into Practice Digest*, vol. 12, No 3, spring 1986; J.F Vinsonhaler and R.K Bass, "A Summary of the Major Studies on CA Dril and Practice," *Educational Technology*, vol. 12, 1972; Dean Jamisor et al., "How Effective Is CAI: A Review of the Research," *Educational Leadership, vol. 33,* 1975 and S.S. Hartley, University of Colorado, "Meta-Analysis of the Effects of Individually Paced Instruction in Mathematics," doctoral dissertation, 1977.

Until recently, mainframe or minicomputers were necessary to accommodate comprehensive and integrated curricula that could cover the entire grade span of an elementary or secondary school. With advances in memory and speed of microcomputers, however, and with the emergence of optical storage media (such as compact disc-read only memory, known as CD-ROM), integrated approaches to CAI no longer require mainframe computers: systems now being marketed by several companies use a microcomputer-based file server located in the same computer laboratory where the children work at terminals. While this change has brought about substantial cost reduction, it has not changed the basic philosophy of CAI, which involves a direct link between student and software and the transfer of basic instructional decisions from teacher to curriculum developer.

Even after the introduction of stand-alone computers (microcomputers), CAI programs remained little more than computerized workbooks. Information was presented on the screen, students were asked to indicate a response, and their response was evaluated. If the student was correct, he or she moved on; if incorrect, similar additional problems were given until correct responses were elicited. Many programs of this type are still used because they have proven effective when used in conjunction with traditional instruction.

Critics of CAI argue that drill and practice tasks could be done just as easily without computers. Another complaint is that CAI promotes passivity on the part of the user.

Advocates argue that many students who have not mastered basic skills can benefit from drill and practice, and that the computer helps to motivate students. In addition, the teacher is freed up to provide initial instruction and to work with individuals or small groups of children.

Hundreds of studies were conducted to determine the effectiveness of CAI. Several researchers have synthesized the results of a number of individual studies conducted at various levels to see if the results held up across studies. These syntheses reveal that elementary level students who received brief daily CAI lessons as a supplement to instruction showed gains equivalent to 1 to 8 months of instruction over their peers who received traditional instruction only.[5] However, when CAI is used as the sole basis for instruction, the results are mixed. Other findings show that CAI is more effective at raising achievement among low-achieving students than for average or high-achieving students, and that students complete material faster with CAI than with traditional instruction, sometimes as much as 40 percent faster. Increases in student attendance, motivation, and attention span have also been reported in most studies. Students who learned on the computer remembered as much of the ma-

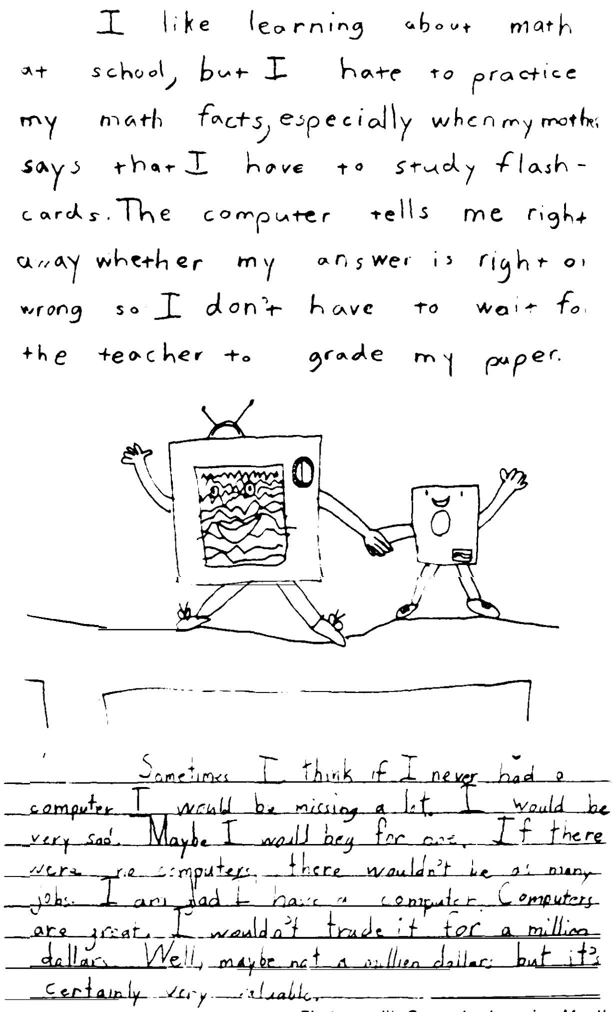


Photo credit: Computer Learning Month

Second graders' views of computers, submitted to the Computer Learning Month contest.

[5] James A. Kulik et al., "Effectiveness of Computer-Based Education in Elementary Schools," *Computers in Human Behavior, vol.* 1, 1985, pp. 59-7'4.

terial as did students who received traditional instruction only. Similar results were revealed in studies of CAI with secondary or college and adult populations, However, the gains in achievement were less significant.[6]

One criticism of CAI is based on a question of equity. Economically disadvantaged children and low-achieving children, many of whom are in federally supported programs (for example, under Chapter 1 of the Education and Consolidation Improvement Act of 1981), use the computer largely for drill and practice in basic skills. Gifted students, as well as children in predominantly white low-income schools, do less CAI and more programming than do students in predominantly minority elementary schools.[7]

It might be argued that low-achieving students are more likely to need the type of support provided by drill and practice. But while low-achieving students do need to master basic skills, they can also benefit from instruction that develops their higher cognitive abilities and learning strategies, Unfortunately, there is a tendency to consider such instruction beyond the ability of low-achieving students and to offer only gifted and high-achieving students such opportunities (with and without the computer).[8]

An exception is the Higher Order Thinking Skills (HOTS) Program developed at the University of Arizona. The program is designed to teach thinking skills to Chapter 1 students, primarily by teaching teachers to ask questions that elicit thinking responses. Teachers are also taught how to use selected software as the focus of Socratic dialogs with students. Early results indicate that Chapter 1 students enrolled in the HOTS program showed substantially greater gains on standardized tests when compared with the national average. According to its developer, the HOTS program is designed to develop thinking abilities among students in Chapter 1 programs."

While the results concerning the effects of CAI are generally favorable, they are based on studies that have been frequently criticized on methodological grounds. One problem, for example, is that the computer treatments in some studies were supplementary while control treatments were not. Students using computers would receive 40 minutes per day in mathematics instruction, 10 of which would be devoted to drill and practice on the computer, while the control students would only receive 30 minutes of instruction. In this case, one cannot be sure that the increased performance of the treatment students was due to the extra 10 minutes per day or to the drill and practice on the computer. Would the results be so significant if the control students received an extra 10 minutes using flash cards or some other form of drill? Other flaws include disproportionate attrition from experimental groups, nonrandom assignment of students to treatments, incommensurable instructional content provided to control groups, and differences in relevant teacher attributes in control and treatment groups. In one review study, 26 out of 51 research reports were deemed unusable because of various methodological problems; however, the positive results of CAI remained stable even after eliminating the flawed studies.[10]

The main problem with the results of this 30-year body of research is that it provides no insight into how CAI produced those learning outcomes. It is only recently that researchers have begun to ask more useful questions, such as how and what students learn when they interact with computer-based instruction. A national field study being led by Henry Becker of The Johns Hopkins University

[6]Dean Jamison et al., "The Effectiveness of Alternative Instructional Media: A Survey," *Review of Educational Research, vol.* 44, *No. 2,* 1974, pp. 1-6; D.N. Hansen, "Computer Assistance With the Educational Process," *Review* of Educational *Research, vol.* 36, *1966,* pp. 588-603; and David B. Thomas, "The Effectiveness of Computer-Assisted Instruction in Secondary *Schools,* " *AEDS Journal*, vol. 12, No. 3, 1979, pp. 103-115.

[7]Henry J. Becker, School *Uses of Microcomputers: Reports From a National Survey* (Baltimore, MD: Center for Social Organization of Schools, The Johns Hopkins University, 1983-1984), issues 1-6; and Elizabeth Reisner, *The Use of Computers in Instruction Supported Under Chapter 1 of the Education Consolidation and Improvement Act* (Washington, DC: Policy Studies Association, 1983).

[8]Beau F. Jones, "Quality and Equality Through Cognitive Instruction," *Educational Leadership*, April 1986, pp. 5-11,

[9]Stanley Pogrow, "Preliminary Report on the Effectiveness of the HOTS Program," unpublished data, 1987.

[10]Henry J. Becker, *The Impact of Computer Use on Children's Learning: What Research Has Shown and What It Has Not* (Baltimore, MD: The Johns Hopkins University, Center for Social Organization of Schools, 1987). *See* also Richard E. Clark, "Evidence for Confounding in Computer-Based Instruction Studies: Analyzing the Meta-Analyses," *Educational Communications and Technology Journal*, vol. 33, 1985, pp. 249-262; and Patrick Suppes and Mona Morningstar, "Computer-Assisted Instruction," *Science*, vol. 166, Oct. 17, 1969, pp. 343-350.

is designed to provide information about the features of various computer-based programs that influence learning. The study has a large and representative sample, will last 3 years or more, and will collect information on how various programs are implemented in different grades and for different subjects each year.

Intelligent CAI

ICAI is a branch of artificial intelligence devoted to developing instruction in curricular areas. The distinctions between CAI and ICAI are subtle and profound. With CAI, instruction is controlled by the developer of the program who determines what is presented, how much information is presented, the order of presentation, and the specific questions to which the student must respond. CAI programs cannot respond to students' questions, responses, or problems that are not specifically designated in advance by the programmer. ICAI programs, on the other hand, theoretically increase students' control over the machine and allow them the opportunity to *learn by doing.* Students interact with the computer rather than merely respond to it in a prespecified way; tutoring is often carried on in dialog form as a response to student input. In addition, ICAI is characterized by a far more thorough and fine-grained analysis of the skills, knowledge, and procedures involved in solving problems in a subject area. The strength of ICAI is not only the substantially more precise and detailed understanding of the nature of learning and problem solving, but also the ability of the program to *articulate,* or make *transparent* that understanding in a form that can be absorbed by the student. ICAI programs specify in detail a mix of three types of knowledge: the declarative knowledge (what), the procedural knowledge (how), and the metacognitive knowledge (thinking about what and how).

ICAI, also referred to as an intelligent tutoring system, can generate and solve problems, store and retrieve data, diagnose students' misconceptions, select appropriate teaching strategies, and carry on dialogs with students. In addition, intelligent tutoring systems employ a wider variety of teaching strategies than are likely to be found in a simple CAI programs. Many intelligent tutoring programs incorporate simulations and / or games that allow students the opportunity to "try out" their evolving models of knowledge in a domain.

Two science programs exemplify these advanced CAI efforts. Batteries and Bulbs, developed by researchers and educators at the Educational Technology Center at the University of California, Irvine, teaches electric circuitry in a way that conveys important aspects of the scientific method. It simulates electric circuit problems and students connect wires on the screen with the objective of lighting a simulated bulb. In addition, the program keeps track of a student's progress, offering assistance if a student consistently makes mistakes on a particular type of problem. Studies of Batteries and Bulbs show that students typically complete the program within an average of 2 hours and exhibit a qualitative understanding of terms such as "current" and "resistance," and a rudimentary understanding of a model of simple electrical circuits.[12]

QUEST is another program in electric circuitry that contains simulation activities, but unlike those in Batteries and Bulbs, the QUEST simulations allow students a variety of solutions to a problem while also designing an arbitrary circuit of their own that they can test through simulation. This aspect of the simulation works because all of the formal electrical laws of circuitry are built into the program and used to determine whether or not a circuit works. In addition, the "proof' or solution of a circuit is broken down and students can walk through a step-by-step, voice-simulated explanation of the proof.

The QUEST learning environment provides students with the opportunity to select from among several instructional approaches. For example, the open-ended exploration option lets students construct and modify circuits and test them with the simulation to see how they work, and with the problem-driven learning option, the system presents a series of problems for students to solve and gives

[11] James L. Poirot and Cathleen A. Norris, "Artificial Intelligence Applications in Education," *The Computing Teacher*, August/September 1987, pp. 8-10. Much of the information in this section is drawn from Christopher J. Dede et al., Massachusetts Education Development Center, "Intelligent Computer-Assisted Instruction: A Review and Assessment of ICAI Research and Its Potential for Education, " unpublished manuscript, 1985.

[12] Alfred Bork, *Personal Computers for Education* (New York, Harper & Row, 1985).

computer-generated voice explanations of the solution when requested by the student. QUEST is based on cognitive research that identified the essential knowledge about electric circuits and the optimal way to teach that knowledge. As of fall 1986, seven students have worked with the complete QUEST program, and after 5 hours of "play," all of the students were able to answer simple questions about circuits and could troubleshoot for opens and shorts-to-ground in series circuits.[13]

Developers of intelligent tutoring systems have attempted to integrate findings from research on how novices learn and how experts solve problems. For example, a feature found in some programs is the *audit trail,* which leaves a record of a student's work as he or she progresses through problem solving. This trail allows students to look back over their own or other students' work and to reflect on the relative value of various approaches to problem solving. The intelligent tutoring system allows students to practice problem solving strategies, and is designed to diagnose errors and provide feedback when a student makes an error or needs help. The tutor does not intervene as long as the student generates correct solution steps. Box 3-A illustrates and describes how an algebra problem is solved with an intelligent tutoring program called the Algebra Tutor.

Similarly, the Geometry Tutor is an intelligent tutoring system that employs audit trails and is currently under study at Carnegie-Mellon University's Advanced Computer Tutoring Project.[14] It provides instruction in proving geometry theorems and focuses on teaching students to problem solve and to plan when they prove theorems. According to the authors of the Geometry Tutor, these skills are seldom emphasized in a standard geometry curriculum. Students often complete a geometry course with only a modest ability to generate proofs and little deep understanding of the nature of proofs. The Geometry Tutor monitors students while they are actually engaged in solving the problems and provides instruction and guidance during the problem solving process. Students do not have to wait until their papers are corrected to receive feedback. Feedback is immediate, precise, instructionally relevant, and based on a far more thorough analysis of problem solving behavior than would be possible with one teacher and a classroom full of students.

The Geometry Tutor was initially tested on a few high school students, some who had no geometry instruction and some who had just completed a high school geometry course. After 10 hours of instruction, all students were able to solve problems that their teachers considered too difficult to assign to their classes. In fact, a student who had almost failed geometry was successful, and the students considered their time on the computer as fun. The researchers are now testing the Geometry Tutor in a high school, comparing the treatment students' performance with that of a control group of students,

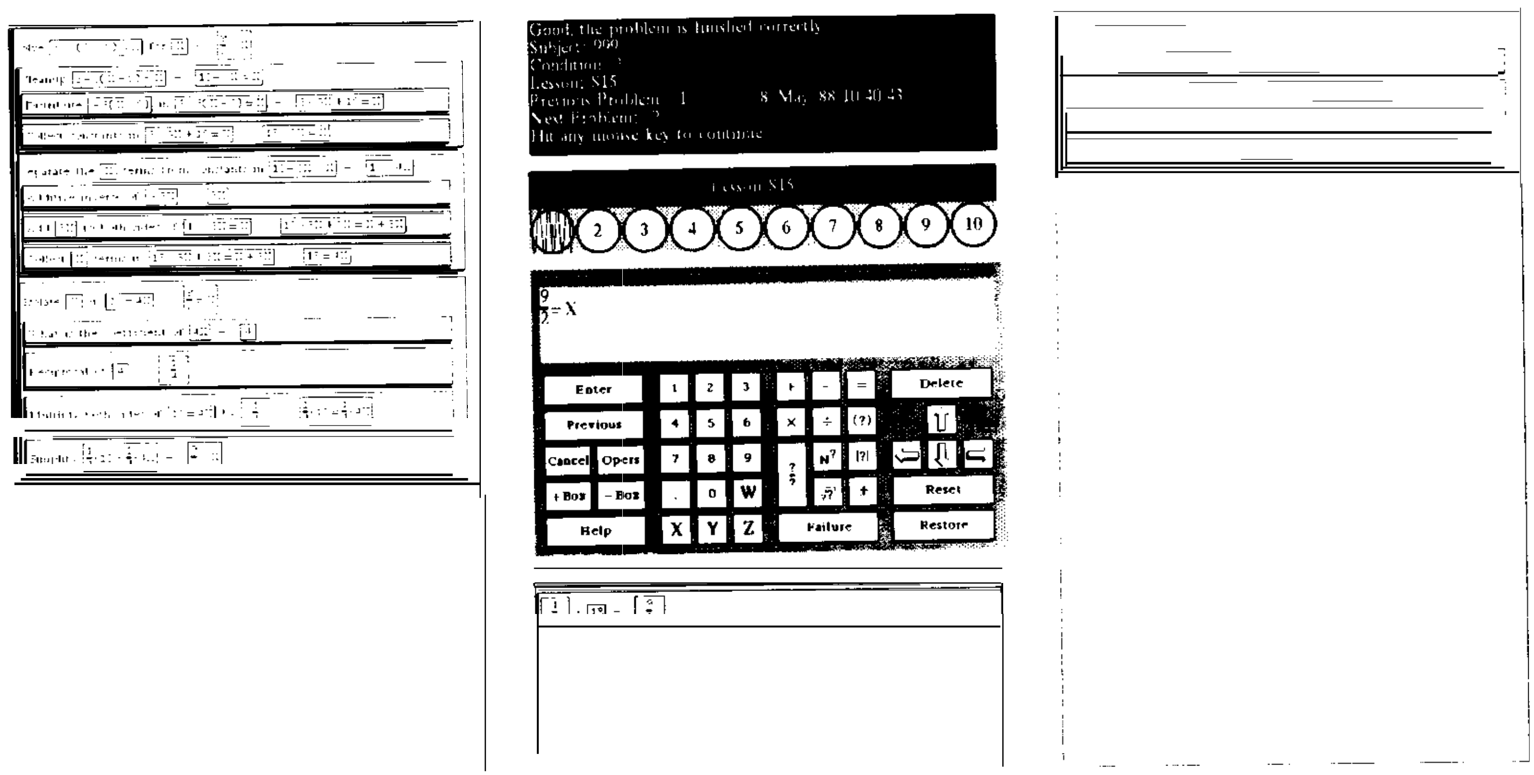
Other intelligent tutoring systems have been developed in a variety of areas. For example, SOPHIE (Sophisticated Instructional Environment)[15] provides students with a way to solve problems by trying out their ideas within the context of a simulated electronics laboratory. The system can answer students' questions, critique their hypotheses regarding why a piece of circuitry equipment is not working, and suggest alternative explanations. SOPHIE's ability to communicate with students depends on its natural language capabilities. The process of programming a computer to understand the ambiguities of natural language (English rather than Fortran) is one of the most intractable problems confronting artificial intelligence researchers today. SOPHIE approaches this problem by replacing conventional categories of grammar, such as nouns and verbs, with categories that represent concepts relevant to the SOPHIE system, such as circuit, transistor, or hypothesis. The system then attends only

[13] Barbara Y. White and J.R. Frederiksen, "Intelligent Tutoring Systems Based Upon Qualitative Model Evolutions," *Proceedings of AAAI-86: The National Conference on Artificial Intelligence* (Philadelphia, PA: American Association of Artificial Intellgience, 1986); and Barbara Y. White and J.R. Frederiksen, *Progressions of Qualitative Models as Foundation for Intelligent Learning Environments,* Report No. 6277 (Cambridge, MA: BBN Laboratories Inc., 1986).

[14] John R. Anderson et al., *The Geometry Tutor* (Pittsburgh, PA; Carnegie-Mellon University, Advanced Computer Tutoring Project, 1985); C.F. Boyle, "The Geometry Tutoring Project in Action," *Educational Leadership,* March 1986; and C.F. Boyle and John R. Anderson, "Acquisition and Automated Instruction of Geometry Proof Skills," paper presented at the Annual Meeting of the American Educational Research Association, New Orleans, 1984.

[15] John Seely Brown et al., "Pedagogical, Natural Language, and Knowledge Engineering Techniques in SOPHIE I, II, and III, " *Intelligent Tutoring Systems,* D. Sleeman and J.S. Brown (eds.) (London: Academic Press, 1982).

Box 3-A.—Solving Problems With the Algebra Tutor



The algebra tutor begins by presenting the student with a problem to solve (solve for X: 3 — 3(X — 5) = X). The student then uses a keypad to enter numbers or operations or selects operations from a menu. He or she can solve the problem immediately or go through a number of substeps. As long as no errors are made, the tutor does not provide any messages. However, if the student makes an error, is unable to go on to the next step, or asks for help, the tutoring system steps in to give immediate feedback or indicate the next step.

As students progress in expertise they begin to group problem solving into larger units (skip steps). The tutoring system is able to recognize skipped steps and adjust its instruction. The figure above shows two approaches to solving the same problem using a different number of steps. The audit trail leaves a record of the student's problem solving strategies.

SOURCE: Robert Milson et al., "The Teacher's Apprentice Project: Building on Algebra Tutor," Carnegie-Mellon University, Pittsburgh, PA, n.d. (Figure reproduced with permission.)

to the concepts it recognizes and tries to make sense of students' responses from those concepts, ignoring other pieces of information.

Impressive as this program might be, it is still a long way from understanding the subtleties of natural language. In fact, most artificial intelligence experts are cautious in their estimates of when, if ever, computers will really be able to cope with natural language.[16] Nonetheless, SOPHIE, along with other natural language-based tutors such as Writer's *Workbench* (AT-&T), *Critique* (IBM), and RINA (created at the artificial intelligence laboratory at the University of California at Los Angeles) have raised the hope that language barriers might be surpassed much the same way computers have overcome human limits to complex mathematical computation.

[16] Terry Winograd, an associate professor of computer science and linguistics at Stanford University, says flatly, "It's not in sight . . . it's not something that can be done by improving and tuning up existing systems.}' In B. Wallraff, "The Literate Computer," *Atlantic Monthly*, vol. 261, No. 1, January 1988, p. 11.

MATHEMATICS AND SCIENCE

Programming

For over 25 years, mathematics educators have advocated the use of programming for teaching mathematics on the grounds that, "Children who program solutions to science and mathematics problems develop a procedural understanding of the fundamental theories of these disciplines."[17]

The effects of using programming to teach mathematics at the elementary and middle school level are mixed, Two studies showed that students who did not use programming outperformed those who did, while two other studies found partial and limited support for programming, At the high school level, four studies found that students who received programming instruction in addition to mathematics instruction performed less well than did students without programming instruction. Two studies found partially positive results.[18]

Another use of programming has been to prepare student teachers to teach facts and concepts of mathematics. From one such experience the researcher observed certain essential difficulties for both teachers and students: 1) students who have problems learning mathematical concepts are likely to find programming concepts equally elusive, 2) additional and more complex cognitive effort is involved in establishing a connection between programming and mathematics, and 3) learning to program requires a great deal of time—time that could be devoted to learning mathematics.[19] Nevertheless, the idea that programming might be an effective vehicle to teach mathematics and to prepare teachers of mathematics is appealing and warrants ongoing study, perhaps along different theoretical lines.[20]

[17] Sylvia A. Shafto, "Programming for Learning in Mathematics and Science," paper presented at the Conference on Innovative Microcomputer Applications in School Programs, Friends School, Baltimore, MD, March 1985. See also National Council of Teachers of Mathematics, The *Impact of Computing Technology on School Mathematics: Report of an NCTM Conference* (Reston, VA: 1984); National Research Council, *Renewing U.S. Mathematics* (Washington, DC: National Academy Press, 1984); Conference Board of the Mathematical Sciences, *The Mathematical Sciences Curriculum K-12: What Is Still Fundamental and What Is Not,* Report to the National Science Board Commission on Precollege Education in Mathematics, Science and Technology (Washington, DC: National Science Foundation, 1983); and Richard J. Shumway, Ohio State University, "Mathematical Concept Learning *Through* Computer Programming: A Survey of Related Research," unpublished manuscript, 1985.

[18] Research on programming in middle schools is reported in D.F. Robitaille et al., "The Effects of Computer Utilization on the Achievement and Attitudes of Ninth-Grade Mathematics Students, " *Journal for Research in Mathematics Education*, vol. 8, 1977, pp. 26-32; and D.T. King, "Research on Computers in Mathematics Education," *The Use of Computers in Mathematics Education Resource Series* (Columbus, OH: ERIC, 1973).

High school results are discussed in S.M. Katz, Temple University, "A Comparison of the Effects of Two Computer Augmented Methods of Instruction With Traditional Methods Upon Achievement of Algebra II Students in a Comprehensive High School," doctoral dissertation, 197 1; R.F. Ronan, University of Michigan, "A Study of the Effectiveness of the Computer When Used as a Teaching and Learning Tool in High School Mathematics, " doctoral dissertation, 1971; and Larry L. Hatfield and Tom E. Kieren, "Computer-Assisted Problem Solving in School Mathematics, "journal *for Research in Mathematics Education, vol. 3,* 1972, pp. *99-112.*

[19] J.B.H. duBoulay, "Teaching Teachers Mathematics Through Programming," *International Journal of Mathematical Education in Science and Technology*, vol. *11, 1980,* pp. 347-360.

[20] See, for example, G. Blume, " A Review of Research on the Effects of Computer Programming on Mathematical Problem Solving, " paper presented at the annual meeting of the American Educational Research Association, New Orleans, 1984.

Employability

Programming has been taught in schools in part to enhance students' employment opportunities after graduation. Researchers at the National Commission for Employment Policy examined the need for computer skills in the work force and concluded that only about 1 percent of the work force will require long periods of computer training (for example, engineers and scientists who design computers, programmers, and system analysts). Another 1 percent will need to be able to write their own programs (for example, some engineers, scientists, technicians, and accountants). The remaining computer users, however, will learn their skills in brief, on-the-job training. These findings suggest that computer programming need not be part of the general curriculum but should be part of a total training package for occupations that require computer use.[21]

Programming and Thinking

Evidence to support the belief that programming develops students' thinking abilities is limited and mixed. One study found that students who learned BASIC did no better than control students on three problem solving subtests: understanding the problem, carrying out the plan, and looking back at the problem.[22] This result is supported by the finding that students who spent a year programming did not differ from control students in planning efficient routes for completing a set of chores.[23] Positive results were found in a large-scale study of LOGO in 15 schools over 7 months. The LOGO students showed significantly more improvement than did non-LOGO students on a test of nonverbal cognitive abilities, exhibited less reliance on their teachers, and showed more independent judgment.[24] In addition, 9- to 1 l-year-old students who received 1 year of instruction in LOGO performed significantly better than control students on two of four problem solving tasks.[25] Another study of 18 6-year-olds found that students who received 12 weeks of instruction in LOGO outperformed students who used the computer to study reading and mathematics in a CAI environment. Students were assessed on measures of creativity, metacognition (ability to monitor and evaluate one's own thinking processes), and on their ability to provide accurate descriptions—an important skill in programming. The two groups did not differ on general measures of cognitive development.[26]

Simulations

Computer programs developed to simulate complex processes that occur in the world are available in several disciplines, including the physical and social sciences. The computer simulates a process through a variety of activities, including writing messages, "acting-out" the process of a phenomenon through illustrations and animation, and drawing graphs based on simulated data. Examples of simulations range from programs that allow students to see how an object behaves in a Newtonian environment, to programs that allow students to play the roles of world leaders making important decisions.

Some simulations are able to represent complex scientific concepts in ways that are impossible without computers. These representations attempt to increase the understanding students have of concepts that have been traditionally quite difficult to grasp.

Physical Sciences

In physics, several pieces of software have been developed to simulate an artificial, frictionless world where the laws of Newtonian physics can be examined. Students can perform experiments and observe results that are not possible in a friction-filled, classroom environment. One study used two computer simulations to diagnose and correct first-year college physics students' misconceptions about speed

[21] Harold Goldstein and Bryna S. Fraser, *Training for Work in the Computer Age: How Workers Who Use Computers Get Their Training* (Washington, DC: National Commission for Employment Policy, 1985).

[22] M. Ford, Arizona State University, "Effects of Computer Programming on the Problem Solving Abilities of Sixth Grade Students," doctoral dissertation, 1984.

[23] Roy D. Pea and D. Midian Kurland, *LOGO Programming and the Development of Planning Skills,* Technical Report No. 16 (New York, NY: Bank Street College of Education, Center for Children and Technology, 1984).

[24] T.A. Swartz et al., "Looking Into a Large-Scale LOGO Project," paper presented at the annual meeting of the American Educational Research Association, New Orleans, 1984.

[25] Joyce Statz, Syracuse University, "The Development of Computer Programming Concepts and Problem Solving Activities Among Ten-Year-Olds Learning LOGO," doctoral dissertation, 1973.

[26] D. Clements and D.F. Gullo, "Effects of Computer Programming on Young Children's Cognition," *Journal of Educational Psychology,* vol. *76, No. 6, 1984.*

and force. In the speed study, racing cars moved across the screen representing relative motion; in the force study, rockets represented the principles of force as related to energy and momentum. Students clearly understood speed better after using the race car program, but did not improve in their understanding of force after working with the rocket programs.[27] High school students working with computer simulations to teach them to solve force and motion problems using Newton's laws of motion learned significantly more than students who did not use the program.[28]

Social Sciences

Noncomputer-based simulations have long been used to raise students' interest in and understanding of social studies. Although research indicates that simulations do not necessarily improve the learning of content or skills beyond conventional instruction, they do seem to increase students' motivation, attitude, and participation. Simulations can also be a more effective way to involve students in decisionmaking processes, and they help convey complex representations of reality better than print materials or classroom lecture and discussion.[29]

Graduate students and faculty at the University of Michigan have developed two computer-mediated social science simulations in which students play the role of national or world leaders engaged in governmental or international affairs. One simulation represents the United States Constitutional Convention. Another, *International Communications Simulation (ICS),* represents the Arab-Israeli conflict. Working in teams of five or more, each student assumes the role of a particular individual or group represented in the conflict, such as the president or king of the country, the defense minister, leader of a guerrilla group, or diplomatic envoy. Teams are dispersed over 15 States and countries, including Mexico, West German, and France; they communicate with each other and with university staff.

Nearly 120 schools have participated in ICS, and informal evaluations have shown a number of positive effects. Students are more motivated to engage in high level critical thinking, have a better understanding of the dynamics of political affairs, appreciate the variety of perspectives on issues, gain experience with the computer and computer-mediated communications, develop insight into the research process, acquire research skills, have an opportunity to practice writing clear, forceful prose, and experience the challenge of making important decisions and the seeing the consequences of their decisions.

There are many types of simulations, but very few have been studied in a research setting. Because of the wide variability in the types of simulations, it would be difficult to generalize about the effects on learning of simulations in general.

Microcomputer-Based Laboratories

One of the more promising uses of computers is as a tool in the science laboratory. Scientists have been using computers to measure and graph phenomena for years, but they are just now making their way into classrooms. These laboratory tools, called microcomputer-based laboratories (MBLs), consist of probes attached to a computer. The probes, interacting with specially designed software, "sense" and measure various phenomena, such as light, heat, temperature, brain waves, pulse rate, and distance.

For example, students working with a sound probe can measure loudness or pitch, and the computer will record, display, analyze, and play back the sounds being measured. Students can try to produce a "smooth" graph by humming a pure note into the microphone—or can compare the graphs of high and low notes. They can measure the wave length of sounds that are an octave apart or compose a tune by plotting a graph of pitches they select. These activities help students to gain a sense of what is meant by the pitch of a tone.

Measurement is not new in school science laboratories. Students spend most of their time measur-

[27] Peter W. Hewson, "Microcomputers, Conceptual Change and the Design of Science Instruction: Examples From Kinematics and Dynamics," *South African Journal of Science*, vol. 80, 1984.

[28] Barbara White, "Designing Computer Games To Help Physics Students Understand Newton's Laws of Motions," *Cognition and Instruction*, vol. 1, No. 1, 1984, pp. 69-108.

[29] Allen Glenn and Lee Ehman, *Computer-Based Education in Social Studies* (Bloomington, IN: Indiana University, Social Studies Development Center and ERIC Clearinghouse for Social Studies/Social Science Education, 1987); and Mark C. Schug and Henry S. Kepner, Jr., "Choosing Computer Simulations in Social Studies," *The Social Studies*, vol. 75, September/October 1984, pp. 211-215.

Photo credit: **Marcia** *Linn, University of California, Berkeley*

Studies of microcomputer-based laboratories (MBLs) indicate that students using them grasp complex scientific concepts at a deeper level of understanding and become more proficient in using graphs than when MBLs are not used.

ing, recording, and graphing phenomena of interest; they often get lost in detail and lose sight of the experiment's focus—the concepts it is designed to convey. The computer can free up students to ask the "What if?" questions that characterize the practicing scientist's world.

A number of studies of MBLs in science laboratories indicate that students using MBLs grasp complex scientific concepts at a deeper level of understanding than when MBLs are not used.[30] In addition, MBLs have been successful in helping students to understand graphs–an important skill in learning science, but one that students often fail to master.

A critical factor in MBL use in the classroom is the way it is used by the teacher. Researchers examined a teacher's approach to using MBLs with various groups of students: one honors class, two average-ability classes, and one class of learning disabled students with average or above average intelligence. The teacher was most structured with the special needs students, discouraging them from exploring the equipment or from trying variations of an activity presented on the laboratory sheets. With the honors students, the teacher allowed substantially more autonomy. All students, except those in the special needs class, showed significant gains in their overall scores in mathematics skills and in understanding scientific concepts. The researchers plan to conduct further studies where learning disabled students use MBLs in an inquiry-based instructional setting.[31]

Educators and scientists generally agree that it is important for students to engage in a process of scientific inquiry. This is often characterized by extensive discussions where students attempt to construct defensible explanations for observable phenomena. Researchers noted that many teachers tended to use MBLs in a very structured way, with little or no discussions of experiments. In some instances, little time was devoted to independent exploration or experimentation. In fact, even projects that trained teachers in the use of inquiry-based instructional strategies for use with a particular computer application showed that teachers reverted to a procedural approach. (See box 3-B.)

Graphing

National test results show that students do poorly at graphing, despite the fact that graphing receives considerable attention in both algebra and geometry classes. Graphs are a powerful way to see functional relationships, for example, relationships between temperature change and time, or pulse rate and exercise. Students who have a solid grasp of graphing skills are more adept at studying changes in physical and social sciences.

The computer is an ideal tool for teaching graphing skills: it provides an instant representation of the relationships between variables and allows students to see graphs in real time as an experiment unfolds. The computer frees students from lower-level tasks (such as plotting points on a graph by hand) and allows them to focus on the more abstract, complex, and intellectually meaningful concepts. Results of studies where students use the computer to develop graphing skills are more consistently positive than any other area of computer use.

[30] Marianne Wiser, *Designing a Microcomputer-Based Laboratory To Induce the Differentiation Between Heat and Temperature in Ninth Graders,* Technical Report No. 85-15 (Cambridge, MA: Harvard University, Educational Technology Center, 1985); and Marcia C. Linn et al., "Cognitive Consequences of Microcomputer-Based Laboratories: Graphing Skills Development," *Journal of Contemporary Educational Psychology, 1986.*

[31] Janice R. Mokros and Deborah L. Levine, Technical Education Research Centers, "The Use and Impact of MBL as a Function of Learner Characteristics," unpublished manuscript, n.d.

Box 3-B.—Microcomputer-Based Laboratories in Practice

Tim Barclay, a researcher at the Technical Education Research Centers (TERC), a laboratory that has taken the lead in developing microcomputer-based laboratories (MBLs) for classroom use, characterizes TERC's view of how MBLs should be used:[1]

> MBLs are tools that have the potential to empower students to be scientists and creative explorers of the world. Being a scientist means investigating the natural world, asking your own questions, finding out 'what-happens-if.' Promoting inquiry in the classroom is a creative act, a process more easily described when it goes awry than when it's nurtured.

Barclay provides illuminating examples of procedural and inquiry classroom environments:

> In one MBL classroom at a large, suburban, junior high school . . . the teacher spent all the introductory time emphasizing a proper sequence of menu choices needed to follow the activity sheet instructions. When the students broke up into small groups, each with their own microcomputer and probes, the task had become 'do it right'. But what was that? They did not remember for sure what was right, and they did not read the instructions on the activity sheets either . . . . They called on the teacher: "What do I do next?" "Is this right?" "Why didn't it work?" Lacking any sense of the nature of the activity, the means had become a meaningless end. Completion was all; understanding was beside the point.
>
> A seventh grade class that used the MBL Sound Unit for several months is an example of tool-empowered inquiry. The two science teachers started by using the unit with their whole class as a group investigation. A single microcomputer was set up at the front of the class. Initially, the teacher posed the problems with the students suggesting how to find an answer and then using the probes to try it.
>
> As the unit progressed, students began to pose questions. The probe and the micro became tools for studying sound—sometimes to quickly show something, other times for an investigation that took up a whole class period. At the end of the sound unit, students did their own projects. These involved research and experiments and reports on topics that ranged from comparing the wave pictures from different musical instruments to analyzing bird songs. The teachers had made MBL their own, used it in their classrooms, and then passed it as a gift to their students to make into their own tool as well.

[1]The following quotes are from Tim Barclay, "Coping With Inquiry," *Hands On!* vol. 10, No. 1, newsletter of the Technical Education Research Centers, Cambridge, MA, 1987.

Sixth-grade students who worked in groups of three used MBLs to produce and observe graphs of motion in real time. The children's task was to produce a particular graph by moving about the room. This was possible because of sonar detectors and software that "sensed" the direction and speed of students' movements. For example, one student would play the role of the "dancer," moving about the room under the direction of two peers who offered advice about which way to move. When a graph was completed, students critiqued their own performance, and often, the dancer would beg for a chance to repeat the graph until he or she was satisfied with the results.[32] Students exhibited a solid understanding of distance and velocity graphs and achieved a mean score of 85 percent correct on a test of related graphing skills. Several other studies using MBLs to develop graphing skills show similar results.[33]

Game-like strategies are a second approach to teaching graphing skills. Programs called *Green Globs* and *Algebra Arcade* were developed to help students understand the relationships between algebraic equations and their corresponding graphs, This is based on the observation that one skill that seems to distinguish bright students with an aptitude for mathematics from other bright students who are less able in mathematics is their ability to look at polynomial equations and to quickly visualize what their graphs would look like.

[32]Ron K. Thornton, *Tools for Scientific Thinking: Microcomputer-Based Laboratories for the Naive* Science Learner, Technical Report 85-6 (Cambridge, MA: Technical Education Research Centers, 1985).

[33]Linn et al., op. cit., footnote 30; and Janice R. Mokros and Robert F. Tinker, "The Impact of Microcomputer-Based Labs on Children's Ability to Interpret Graphs," *Journal of Research in Science Teaching, vol. 24, No. 4, 1987,* pp. 369-383.

These computerized graphing games develop this ability by asking students to write an appropriate equation for a given graph. In *Green Globs*, the computer displays coordinate axes with 13 green globs scattered randomly on the screen. The student's task is to hit all of the globs with graphs that are generated by typing in equations. When a glob is hit, it explodes and disappears. The student's equation is instantly displayed in graphic form, so the student receives immediate feedback on his or her ideas (see figure 3-2).

One evaluation showed that students who regularly used *Green Globs* increased their graphing abilities more than control students who were unintentionally exposed to the graphing games for a short amount of time.[34]

[34] Sharon Dugdale and D. Kibbey, University of Illinois, Urbana-Champaign, "Prototype Microcomputer Courseware for Teaching High School Algebra," SED80-12449, final report to the National Science Foundation, 1980.

Algebra Arcade–an outgrowth of the *Green Globs* graphing program–was used with bright, female high school students who exhibited mathematics anxiety. Students who used the computer in this study were much more likely to explore relationships, try out ideas, try more experiments, and ask more questions, such as "If we made the numbers on the coordinates small by making the scale spaces large, would it speed up our calculations? What would we miss?" These results carried over to science laboratory investigations. The computer students were more likely to explore the differences in the interplay between phenomena and their representations in models, data tables, and graphs.[35]

[35] Mary Budd Rowe, University of Florida, Gainesville, "Computer Graphics in the Science Laboratory: An Experiment," unpublished manuscript, 1986.

MULTIMEDIA PROGRAMS

Several software programs have been developed in conjunction with videodisc and other media to provide learning environments in mathematics and science for students in grades 4-6. The ***Voyage** of the Mimi* was developed by researchers at the Bank Street College of Education, Center for Children and Technology. The instructional materials include learning modules, each with a different type of software and assorted print materials. The software models a variety of adult uses of technology, including a training simulation, a microworld, a programming environment, and a microcomputer-based physics laboratory. All of the video programs are closed-captioned in two languages: English and Spanish, and since one of the main characters is deaf, signing is used throughout. A key element of the design of the ***Voyage** of the Mimi* was the involvement of teachers throughout all phases of development.[36]

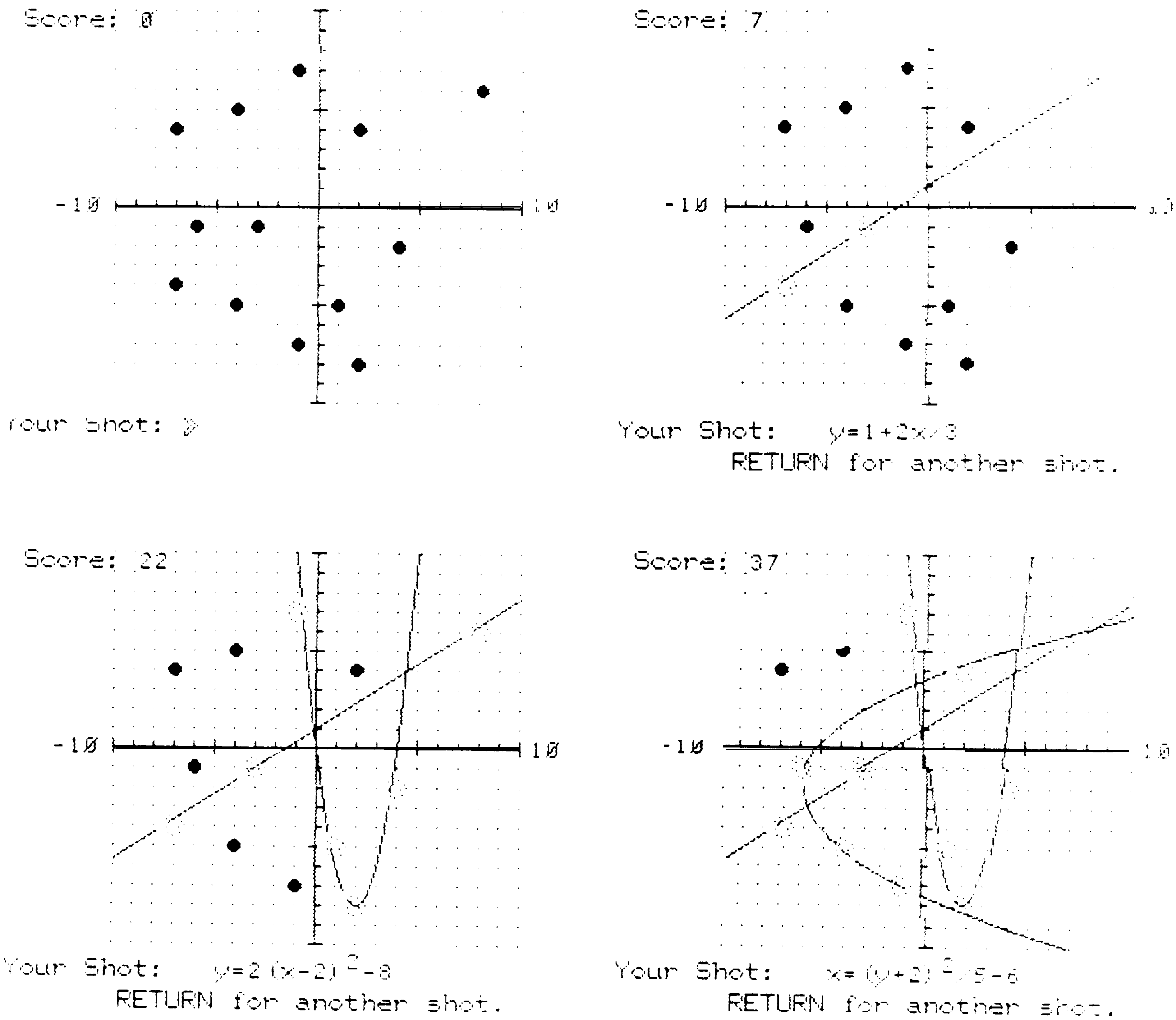
[36] Cynthia Char and Jan Hawkins, "Charting the Course: Involving Teachers in the Formative Research and Design of 'The Voyage if the Mimi'," *Children and Microcomputers: Theory, Research, and Development From Bank* Street College's *Center for Children and Technology* (working title), Roy Pea and Karen Sheingold (eds.) (Norwood, NJ: Ablex Publishing, in press).

The video documentary segments show scientists in their actual working environment; students get a sense of the scientific processes and procedures as they are used in real work situations. The learning modules include: simulation games of navigation problems; an MBL package for gathering and graphing temperature, sound, and light data; and a com-

Photo credit: **Agency** *for* **Instructional** *Technology*

While studying with the *Voyage of the Mimi* in school, Colby Leonard became "hooked" on science and built this bioshelter, a complete ecosystem, in his backyard.

Figure 3-2.—Graphing Equations Using the Computer



The student types in equations, which are graphed by the computer. The glob explode as they are hit by the graphs. Shown is the initial display of 13 globs, followed by the student's first three shots.

SOURCE: Displays of computer screens from Green *Globs* by Sharon Dugdale and David Kirby, reprinted with permission of the authors. For additional information see, Sharon Dugdale, "Green Globs: A Microcomputer Application for Graphing of Equations," *Mathematics Teacher,* **March 1982.**

puter simulation that allows students to explore the food chain, species populations, and the impact of human intervention on ecosystems. The software is accompanied by teacher guides that include a comprehensive discussion of whales (one of the major topics) and suggestions for classroom activities.

The learning modules were field tested over a 2-year period with 82 teachers and staff developers from 13 districts across the country to obtain their reactions to the videotape and software. The researchers observed the use of the materials in classrooms, conducted student and teacher interviews, and collected daily logs maintained by teachers regarding their perceptions of the materials as they were being tried out. The researchers conducted 1 week training sessions for teachers in the principles of inquiry-based instruction.

The integration of inquiry teaching strategies with the use of technology was the primary goal of the Mimi project. Inquiry teaching promotes an environment that tolerates ambiguity and encourages students' questions. The researchers found that few teachers were able to adopt or sustain a style of teaching that encouraged inquiry. Teachers tended to ask the majority of the questions and rewarded students for guessing correctly. Teachers required continual help in maintaining a classroom climate that emphasized reasoning rather than right answers, and only teachers who had experience in inquiry-based instruction used the materials in an open-ended way. The researchers found that it was important to provide training in the scientific concepts covered in the materials and to give teachers rich and varied suggestions for classroom activities. All teachers using the Mimi materials reported that they intend to use them again and recommended the materials to other teachers.

~[7]Margaret A. Honey et al., "Teaching Technology: Creating Environments for Change," paper presented at the American Educational Research Association, Washington, DC, 1987.

DATABASE MANAGEMENT

Students in some classrooms use database management software to store, update, retrieve, organize, sort, format, and perform computations on data. Unfortunately, while there are numerous anecdotal reports enthusiastically describing their use in classrooms across the country, there is very little research documenting the effects of such tools in learning.

One of the few studies conducted on the use of databases involved 14 teachers and 665 students in grades 7 through 12. One group of students used a computerized database (PFS: *Curriculum Data Bases for U.S. History and for U.S. Government),* while the control students used the same curriculum-specific data printed on 4" x 6" index cards housed in plastic file boxes.

The key difference between the activities engaged in by the two groups was in the level of structure. Students in the computer group received detailed instruction in how to use the computerized database system to solve problems, define information, develop data retrieval specifications, interpret and evaluate retrieved data, and revise retrieval specifications. The control students did not receive similar step-by-step guidance in noncomputerized data management. In addition, the design of the database program imposed more of a structure in manipulating data than was possible with the students who used the index card system.

In a carefully controlled experimental design to test information processing skills, students using the computer database program in concert with structured activities significantly outperformed the control students. The specific abilities measured on the Information Processing Scale were: I) to recognize sufficient information to solve a given problem, 2) to recognize whether the information presented was relevant to a given problem, and 3) to discriminate between efficient and inefficient organizations of information to solve a given problem. '8

[38]Charles White, Indiana University, "The Impact of ***Structured*** Activities With a Computer-Based File Management Program on Selected Information-Processing Skills," doctoral dissertation, 1986. See also Charles White, "Developing Information-Processing Skills Through Structured Activities With a Computerized File-Management Program," *Journal of Educational Computing Research, vol. 3, No. 1, 1987.*

The use of database systems is likely to increase, especially as this tool will continue to play a central role in business management, science, and industry. Skills that students need in order to use these systems include the ability to:

- define a problem in specific terms, perhaps breaking it up into several small problems;
- identify specific data needed to address that problem;
- locate and extract relevant data from the larger collection of data;
- put the data in a useful order (e.g., by size, date, age);
- organize printed lists or arrangements of the data;
- use the information obtained to identify patterns such as relationships or trends (as well as cases that depart from the patterns);
- identify further information needed in order to explain, interpret or investigate cause and effect relationships; and
- communicate findings to others."[39]

[39]Beverly Hunter, "Knowledge-Creative Learning With Data Bases," *Social Education, vol. 51, No. 1, 1987. See* also M. Rothman, "Using the Microcomputer to Study the Anatomv of Revolution, " *The Computing Teacher, vol. 10,* September 1982; Tama Traberman, "Using Interactive Computer Techniques to Develop Global Understanding," *The Computing Teacher,* September 1983; and D.M. Morrison and J. Walters, "IMMIGRANT: A Social Studies Simulation for Apple-Works," *Computers in the Classroom: Experiences Teaching With Flexible Took, C.* Thompson and L. Vaughn (eels.) (Chelmsford, MA: Northeast Regional Exchange, Inc., 1986)

WORD PROCESSING

Word processors offer writers ease in editing, neat printed copy, and tend to make the process of writing more public. They often incorporate features that hyphenate words and check on spelling, and some of the more complex correction programs comment on the screen about style and grammar, while others catch errors and report them to the writer. Students' writing does not necessarily improve merely by using the word processor. While students may be inclined to write more text, and enjoy writing more when they use a computer, students' corrections are often mechanical rather than substantive.[40]

A number of key differences in the writing and revision process of expert and novice writers have emerged from research on writing. Experienced writers revise extensively, while beginning writers tend to make superficial changes, such as spelling or word choices. In fact, beginning writers often do not even read over their text when asked to revise, but rewrite from memory. Revision is a complex cognitive process.[41] Young or novice writers may not know what to do when asked to revise. Revision requires writers to evaluate their writing, diagnose problems, and figure out how to correct the problems. Merely easing the physical requirements of writing does little to ensure that these cognitive abilities are developed.

Researchers have begun to identify key strategies that seem to be essential for reading, critiquing, and improving one's own written work, Some of these strategies are being incorporated into software programs for writing. For example, a program called Catch encourages students to take the point of view of the reader as they revise and prompts students to focus on the meaning of a passage rather than on its more superficial aspects. Studies with middle school students showed that students using the Catch software made more revisions from the original text when compared with students who used only a word processor. Revising in this manner also means that more changes can be made within the body of the text rather than by adding changes at the end. These results are particularly significant,

[40]Colette A. Daiute, "Psycholinguistic Foundations of the Writing Process, " *Research in the Teaching of English, 1981,* pp. 5-22; Colette A. Daiute, "The Effects of Automatic Prompting in Young Writers," interim reports to the Spencer Foundation, 1981, 1983. See also R.M. Collier, "The Word Processor and Revision Strategies," *College Composition and Communication,* vol. 34, *1983,* pp. 149-155; and L. Bridwell et al., "Revising and Computing: Case Studies of Student Writers," *The Acquisition of Written Language: Revision and Response,* S. Freedman (cd.) (Norwood, NJ: Ablex, 1985), pp. 172-194.

[41]Colette A. Daiute, "Physical and Cognitive Factors in Revising: Insights From Studies With Computers," *Research in the Teaching of English,* vol. 20, 1986, pp. 141-159; Colette A. Daiute, *Writing and Computers (Reading,* MA: Addison-Wesley, *1985);* and L. Flower et al., "Detection, Diagnosis, and the Strategies of Revision," College *Composition and Communication,* vol. 37, 1986, pp. 16,55.

because it is rare for beginning writers to revise in this fashion, regardless of their age.[42]

Findings concerning how learning disabled students use the word processor are consistent with those from studies of regular students. In a year-long study, learning disabled students who used the word processor as a supplement to writing instruction made significant gains in their writing ability compared to a control group that did not receive the special intervention.[43] It appears that the word processor alone does not significantly enhance the writing abilities of either regular or learning disabled students. But when coupled with instruction in strategies for writing (for example, strategies for generating ideas or for revising) tend to produce more fluency in writing and revisions that affect meaning.[44]

[42]Colette A. Daiute, "Rewriting, Revising and Recopy ing," paper presented at the meeting of the American Educational Research Association, New Orleans, April 1984; and Colette A. Daiute and John Kruidenier, "A Self-Questioning Strategy To Increase Young Writers' Revising Processes," *Applied Psycholinguistics,* vol. 6, 1985, pp. 307-318.

[43]L.B. Kershner and B.J. Kistinger, "Language Processing/Word Processing: Written Expression, Computers and Learning Disabled Students," *Learning Disability Quarterly,* vol. 7, 1984, pp. 329-335. See also S. Graham and Charles MacArthur, "Improving Learning Disabled Students' Skills at Revising Essays Produced on a Word Processor: Self-Instructional Strategy Training, " unpublished raw data, 1987.

[44]See, for example, Catherine C. Morocco and S.B. Neuman, *Teachers, Children and the Magical Writing Machine* (Newton, MA: E. C. C., 1987); C. Morocco and S.B. Neuman, "Word Processors and the Acquisitions of Writing *Strategies," Journal of Learning Disabilities,* vol. 19, 1986, pp. 243-247; E. Ellis and E. Sabornie, "Effective Instruction With Microcomputers: Promises, Practices and Preliminary Findings," *Focus on Exceptional Children,* vol. 19, No. 4, 1986, pp. 1-16; Charles A. MacArthur et al., *Learning Disabled Students' Composing With Three Methods: Handwriting, Dictation and Word Processing,* Research Report No. 109 (College Park, MD: University of Maryland, Institute for the Study of Exceptional Children and Youth, 1986); and S.B. Neuman and C. Morocco, *Two Hands is Hard for Me: Keyboarding and Learning Disabled Children* (Newton, MA: University of Lowell, Education Development Center, 1986).

LANGUAGE ARTS

Reading Comprehension

According to reading theory, comprehension is dependent on several cognitive processes, including decoding, word recognition, and knowledge. If a reader is deficient in one or more of these aspects, the ability to read and understand will be impaired. Early instruction in reading typically aims to develop proficiency in the subprocesses, so that learners can devote intellectual activity to higher levels of thinking. While the vast majority of computer-based learning materials treat the simplest of language tasks—spelling and vocabulary—there are some products that aim at more complex aspects of comprehension.

In a study of 108 low-achieving, poor black children, it was found that students who used two reading programs outperformed a control group in both accuracy and efficiency of decoding and recognition.[45] These programs, called *Construct-a-Word* and *Hint-and-Hunt,* have students compose words from letter strings and identify words with vowels and vowel combinations. The improvements for low-ability students were substantial–they gained over 1 year on standardized tests—but students who were already adequate in their decoding skills did not show any changes. The findings were essentially the same for the development of students' ability to comprehend phrases and sentences.

The hypothesis that a computer can enable readers to understand text according to their individual needs for assistance in comprehension has been tested in a controlled experiment; results showed that students who received various forms of comprehension assistance—without asking for such assistance—outperformed other groups.[46] In addition, computers have been paired with speech synthesizers to assist both regular and special education students in understanding words or pairs of words. Among the perceived advantages of computer-aided reading, researchers point out that: 1) disabled readers can conveniently and privately receive the decoding help they need without an indi-

[45]Steven F. Roth and Isabel L. Beck, "Theoretical and Instructional Implications of the Assessment of Two Microcomputer Word Recognition Programs," *Reading Research Quarterly,* vol. 22, 1987, pp. 197-218.

[46]David Reinking and Robert Schreiner, "The Effects of Computer-Mediated Text on Measures of Reading Comprehension and Reading Behavior," *Reading Research Quarterly,* vol. 10, No. 5, 1985, pp. 536-551.

vidual human tutor or teacher, 2) speech feedback can be tailored to match the unique needs of each student, 3) a wider variety of reading materials can be used, 4) reading can become a means for gaining knowledge, 5) the amount of actual time spent reading is maximized because the reader/student does not have to wait for the teacher to explain an unknown word or spend lengthy periods trying to identify difficult words, 6) students are more likely to experience a feeling of success as they progress through the material and easily gain knowledge of new words and increased information from the passages, and 7) the computer maintains a detailed record of the student's reading and requests for assistance, thereby providing researchers with useful information for the study of comprehension problems.[47]

In one study of the impact of computer-aided reading on reading disabled students aged 8 to 18, it was demonstrated that the students enjoyed using the system and showed significant short-term gains in word recognition and comprehension when audio feedback was available.[48]

In another pilot study, six students enrolled in an adult education center were observed individually and interviewed by researchers as they used a computer-aided reading system. The researchers asked the participants to alternate reading the passages with and without the use of the speech feedback. One of the more interesting findings was that use of the speech feedback significantly reduced the level of stress the participants exhibited when struggling with reading in the unaided situation. The participants commented about how hard it was to read and asked if they had to continue. The researchers reported that much of the stress disappeared when they used the speech feedback. The students all indicated that it was much easier to read when they had the assistance and inquired if it were possible to obtain such a system for their personal use and for use by their children or spouses. In addition, many students indicated that they would read more if such a system were available.[49]

Vocabulary and Grammar

Staff at the Houston Independent School District used speech synthesizers in their locally-developed computer courseware designed to assist limited English proficient students in learning English vocabulary and grammar. The district resorted to developing their own computer-based instructional system when they were unable to locate commercially-developed materials suitable for their 34,000 limited English proficient students. The resulting courseware incorporates dynamic, high resolution graphics and digitized speech within a variety of simulation and game programs and is intended for students in kindergarten through fifth grades. Results of one of the 14 courseware units showed that the treatment group scored significantly better than did control students.[50]

Writing, Reading, and Spelling

One of the most widely marketed computer-based educational programs using digitized speech is IBM's *Writing to Read*. It is a multicomponent system involving kindergarten and first grade children in typing words, reading while listening to tape-recorded stories, and listening to computerized speech designed to teach basic phonics.

The evaluation of *Writing to Read* was one of the most comprehensive studies conducted at the kindergarten and first grade levels. A nationwide sample of 35 *Writing to Read* schools and 25 non-*Writing to Read* schools was assessed, representing over 200 teachers and 7,000 children. Writing, reading, and spelling skills were measured.[51]

The results showed that the *Writing to Read* students performed significantly better in writing than

W. 'George W et al., Center for the Study of Reading, University of Illinois, Urbana-Champaign, "Computer Aided Reading With Illiterate Adults, " unpublished manuscript, *1987*.

'R. "*Reading* l., "Readin and Remediation Reme the Aid of Computer Speech," *Behavior Research Methods, Instruments and* anc vol. 18, No. 2, 1986, pp. 93-99; and R. Olson and B. Wise, "Computer Speech in Reading Instruction," Instruction and *Reading: R for ng: Issu and Theory* D. *Practice* (cd.) einki York, NY: Teachers College Press, 1987).

"George V. M David e anc "computer Aided puter adir An Environment for Developmental Research, " paper presented at the Society for Research on Child Development, Toronto, Canada, 1985.

the Anderson, *English as a Second Language: d Language Cou. me its u Report* (Houston, TX: Houston Independent School n and 1985).

'lRichard T. Murphy and Lola Rhea d Lola Rhea App *of Evaluation Yo to Read Instructional System 1982-84* (Princeton, (F Educational Testing Service, 1984).

the control students in both kindergarten and first grade (table 3-l). *Writing to Read* students in the first grade 1 year after using the program still outperformed non-Writing to Read students, but the differences between the two groups narrowed substantially. In fact, while the non-Writing to *Read* scores increased over the year, the *Writing to Read* **scores** decreased slightly. The effects of the program were consistent across all ethnic groups, with the exception of Oriental students where the non-*Writing to Read* students performed slightly better than the *Writing to Read* students. Classroom observations revealed that students were delighted with their writing and eager to read their passages aloud to visitors.

The results for reading were less impressive. Children in both the *non-Writing to Read* and the *Writing to Read* program progressed at about the same pace.

Table 3-1 .–Mean Writing Scores by Group (percent)

Group	Writing to Read	Non-Writing to Read
Kindergarten	4.5	3.1
First grade	6.6	4.9
First grade after *Writing* to *Read*	*6.5*	*5.7*

SOURCE: Richard T. Murphy and Lola Rhea Appel, ***Evaluation of the Writing to Read instructional System,*** **1982-84 (Princeton, NJ: Educational Testing Service, 1984).**

Spelling was assessed in a less systematic fashion, but results showed that the performance of both groups was quite similar: although it uses a phonetic alphabet, *Writing to Read* did not appear to have a negative affect on students' spelling.

Photo credit: IBM

The IBM *Writing to Read* Project has been adopted by many schools as a way of improving early reading and writing skills.

A survey of teachers showed that *Writing to Read* teachers rated the program far more effective for above-average students than for average or below-average students. Unfortunately, the study suffered from a problem found in several other studies described in this chapter—the *Writing to Read* students spent more time in reading instruction than did the control groups.[52] A larger percentage of teachers involved in the *Writing to Read* program reported spending more time on reading instruction than in previous years (58.2 percent) than did the non- *Writing to Read* teachers (26.7 percent). In writing, 80,5 percent of the *Writing to Read* teachers indicated that they spent more time on writing than in the previous years as compared with 30.5 percent in the non-Writing *to Read* classrooms. On the one hand, any program that engages kindergarten and first-grade children in writing activities is desirable, but the positive effects found in the program may be attributable to increased time rather than to any aspect of the *Writing to Read* program.

Researchers at Vanderbilt University's Learning Technology Center have shown that the speech synthesizer can be effective in providing spelling instruction. In traditional approaches to spelling instruction, the teacher says the word, students write it, and then the written word is compared to the correctly spelled word. Some computerized approaches have students type the word from a model on the screen, then type the same word after the model is removed, and then enter the word into a sentence. Most studies using variations on this instructional theme have shown either no significant difference between computer and noncomputer groups and/or limited success with either group.[53]

The Vanderbilt researchers argue that these approaches were unsuccessful because the student could rely on spelling the word by engaging short-term memory. They investigated presenting the spelling words to students by using a voice simulator, which, they believe, activates long-term memory. When the student spells the word incorrectly, the computer visually and auditorially imitates the student's error and provides the correct spelling, so that the student can compare the two, Results of studies using this approach show that computer-using students achieved an accuracy of over 90 percent on lists of spelling words; in addition, the computer students averaged over 30 percent more correctly spelled words than when they used traditional procedures.[54]

[52]Olson and Wise, op. cit., footnote 48.

[53]G. Fitzgerald et al., "Computer-Assisted Instruction for Students with Attentional Difficulties," *Journal of Learning Disabilities*, vol. 19, *No. 6, 1986*, pp. 376-379; P.A. McDermott and M.W. Watkins, "Computerized vs. Conventional Remedial Instruction for Learning-Disabled Pupils," *Journal of Special Education, vol. 1, No. 1,* 1983; Jacqueline Haynes et al., *Effect of Computer-Assisted Instruction on Learning Disabled Readers' Metacognition and Learning of New Words*, Research Report No. 101 (College Park, MD: University of Maryland, Institute for the Study of Exceptional Children and Youth, 1984).

[54]Ted Hasselbring, "Remediating Spelling Problems in Learning-Handicapped Students Through the Use of Microcomputers,)' *Educational Technology*, *vol.* 22, 1982, pp. 31-32; and Ted Hasselbring, "Using a Microcomputer for Imitating Student Errors to Improve Spelling Performance, "*Computers, Reading and Language Arts,* vol. 4, 1984, pp. 12-14. See also Ted Hasselbring, "Effective Computer Use in Special Education: What Does the Research Tell Us?" a paper presented at Funder Forum, sponsored by Apple Computer, Inc., Cupertino, CA, 1987.

ELECTRONIC NETWORKS

Electronic networks allow individuals or groups to communicate with one another using computers that are connected through local area networks (LANs) or through telephone lines. Electronic networks are being used in every subject area and at all but the earliest grade levels. A good example of a computer network used in education is the Computer Chronicles Newswire project, where third and fourth grade students in Alaska communicate with students in California about events and issues in their school and community. Each site publishes a newspaper that consists of articles selected by the student editorial board. Through this process, students engaged in dialogs with others from a different culture, struggled with communicating clearly in writing, and gained valuable experience in evaluating and revising compositions.[55] Similarly, in a computer network called De Orilla a Orilla (From Shore to Shore), limited and non-English speaking students in New England and California are paired

[55]M.M. Riel, "The Computer Chronicles Newswire: A Functional Learning Environment for Acquiring Literacy *Skills,* "*Journal of Educational Computing Research*, vol. 1, 1985, pp. 317-337.

with Spanish-speaking students in Mexico and Puerto Rico for the purpose of improving their writing skills.[56] Another international computer communications network involves students in eight secondary and college groups in the United States, Japan, and Israel. The project is designed to permit students from different cultures to use one another as resources for learning about their social, cultural, and physical worlds. Participating students explore topics such as peaceful alternatives to war, how schools prepare students for careers, peer violence, and water supply systems.[57]

Children in fourth through sixth grades are now collecting, recording, and comparing the range of acidity or alkalinity of common liquids, including rain, using an electronic network established through a joint venture among the Technical Education Research Centers, the National Geographic Society, and the National Science Foundation.

This National Geographic Kids Network allows students to share information they collect with each other and a specially designated scientist on topics such as weather forecasting, water pollution, and food growing. A powerful central computer is used to summarize data supplied by the students and to create charts, maps, and other presentations which are sent back to the students. In their classrooms, students then analyze patterns and trends in their data and compare their results with children in other schools across the Nation. Results from a pilot study of this network's first year of operation were very promising.[58]

Another science project using electronic communications was tested by sixth-grade students and teachers in New York City.[59] This project, called Earth Lab, allowed students to collect, analyze,

[56] According to Sayers and Brown, initiators of the project, "Students in bilingual education programs need authentic contexts for mother-tongue writing if they are to develop and maintain basic literacy skills and then transfer them to English academic settings." Sayers considers computer networks to be a "perfect fit" with the special needs of bilingual students. See Dennis Sayers and K. Brown, "Bilingual Education, Second Language Learning and Telecommunication: A Perfect Fit," *CALL Digest,* vol. 3, No. 5, 1987; and Dennis Sayers, "Bilingual Sister Classes in Computer Writing Networks," unpublished manuscript, 1987.

[57] M.M. Riel, "Intercultural Learning Network," CALL *Digest,* vol. 3, No. 5, 1987.

[58] See Technical Education Research Centers, Cambridge, MA, "National Geographic Society Kids Network Project Annual Report, October 1, 1986-September 30, 1987."

[59] David Newman et al., *Earth Lab: Progress Report* (New York, NY: Bank Street College of Education, 1987).

Photo credit: Steve Raymer, National Geographic Society

In the Kids Network Project, students collect water for PH testing as a part of the acid rain unit.

Photo credit: Cecilia Lenk, Technical Education Resource Centers

Mapping activities are important as students compare their data with that of other student scientists on the Network.

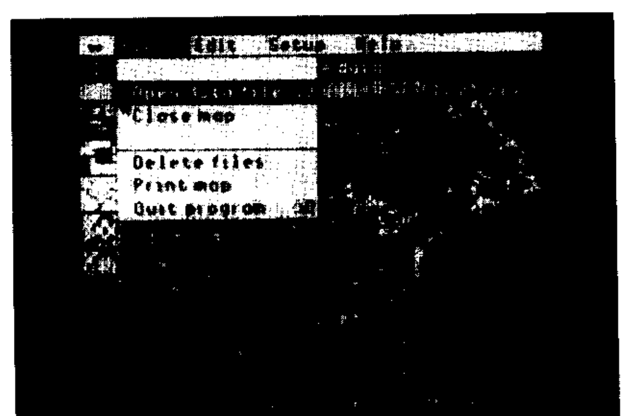


Photo credit: Sara Witherow, Technical Education Resource Centers

The mapping software is used to find the "global address," or latitude and longitude, of any place on the map, to zoom-in on areas for details, and to overlay Network data on the map.

share, and write about their own science research projects on geographic systems, such as convection, the water cycle, and weather forecasting. Earth Lab was designed for teachers who have little or no prior experience with computers or the complexities of real world science,

Teachers in remote rural areas are using electronic networks to discuss the issues and problems they face in teaching science. The Educational Technology Center at Harvard University has organized and is studying a network designed to encourage teachers to pose and respond to each other's questions about science instruction and to participate in discussions originated by "guest" scientists and educators. Early results indicate that more isolated teachers use the network more frequently, and that all teachers found the information obtained through the network valuable.

CONCLUSIONS

The "natural experiment" with interactive technologies that began in American schools 30 years ago has spawned a new and growing family of research and evaluation studies, which have already borne a substantial harvest of results and hypotheses that warrant ongoing investigation. While in the early days the focus was almost exclusively on mainframe and minicomputer CAI systems, today's research agenda spans a much wider spectrum of technologies and explores their effects on the full array of educational processes. As important, the advent of interactive educational technologies has stimulated and facilitated new research forays into the cognitive workings of the human mind: *technologies for learning* are helping us to understand the *technology of learning*. It is hoped that this new knowledge will eventually translate to products and processes that can expand conventional limits to human information processing.

OTA recognizes that research in this complex field of education yields findings that may be divergent or ambiguous. It should be remembered that many of the research models that map relationships between inputs and educational productivity have been imported from the worlds of science and business, where it is easier to define outcomes and identify the production technology. Ironically, while business firms might have opted for a rigorous experimental approach to office automation, using familiar indicators such as profits and losses to determine optimal technologies, they chose instead a strategy of *learning--by-doing:* hardware and software were installed and experience dictated the direction of change and improvement. While it is true that schools do not enjoy the decisionmaking and resource allocation flexibility of business firms, it is also true that the effective integration of new technologies will require an atmosphere of openness to trial, error, and correction.

The analogy with business and industry is instructive for another reason. Perhaps the single most important distinction between these sectors' involvement with interactive technology is their mode of financing and governance. Education is a public enterprise funded at the State and local level, and resource allocation is necessarily highly politicized. Unlike business firms which, in theory at least, learn about the efficiency of their operations from the market, and which enjoy considerable latitude in adjusting to new technologies and new market forces, schools operate in an environment where inefficiencies are neither obvious nor easily remedied. The paradox is that while the exigencies of school budgeting and governance heighten the need for careful planning and efficient utilization of scarce resources, the complexities of education pose significant limitations to the application of simple efficiency criteria. It is not by simple oversight that virtually all of the studies cited in this chapter omitted consideration of the *costs* of the technologies in question. Nevertheless, while educators and other users of these technologies may be concerned primarily with their effects on children's school experiences, policymakers are facing growing pressure to demonstrate that those benefits justify their costs. In an era when performance, productivity, and efficiency of our educational institutions are priority issues, it is inevitable that the cost-effectiveness of new technologies should be questioned. This subject is addressed in the next chapter.