

Changing How and What Children Learn in School with Computer-Based Technologies

Jeremy Roschelle, Roy Pea, Christopher Hoadley, Douglas Gordin, Barbara Means

SRI International, Menlo Park CA

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Abstract

Schools today face ever-increasing demands in their attempt to ensure that students are well-equipped to enter the workforce and navigate a complex world. Research indicates that computer technology can help support learning, and that it is especially useful in developing the higher order skills of critical thinking, analysis, and scientific inquiry. But the mere presence of computers in the classroom does not assure their effective use. Some computer applications have been shown to be more successful than others, and many factors influence how well even the most promising applications are implemented.

This article explores the various ways computer technology can be used to improve how and what children learn in the classroom. Several examples of computer-based applications are highlighted to illustrate ways technology can enhance how children learn by supporting four fundamental characteristics of learning: (1) active engagement, (2) participation in groups, (3) frequent interaction and feedback, and (4) connections to real-world contexts. Additional examples illustrate ways technology can expand what children learn by helping them understand core concepts in subjects like math, science, and literacy. Research indicates, however, that the use of technology as an effective learning tool is more likely to take place when embedded in a broader education reform movement that includes improvements in teacher training, curriculum, student assessment, and a school's capacity for change. To help inform decisions about the future role of computers in the classroom, the article concludes that further research is needed to identify the uses that most effectively support learning and the conditions required for successful implementation.

A teacher from the late nineteenth century entering a typical classroom today would find most things quite familiar: chalk and talk, as well as desks and texts predominate now as they did then. Yet this nineteenth century teacher would be shocked at the demands of today's curricula. For example, just a century ago, little more was expected of high school students than to recite famous texts, to recount simple scientific facts, and to solve basic arithmetic problems. Only 3.5% of students were expected to learn algebra before completing high school.¹ Today, all high school students are expected to be able to read and understand unfamiliar text,² and to become competent in the processes of scientific inquiry and mathematics problem-solving, including algebra.³ This trend of rising expectations is accelerating with the explosion of knowledge now available to the public and the growing demands of the workplace.⁴ More and more students will have to learn to navigate through large amounts of information, and to master calculus and other complicated subjects in order to participate fully in an increasingly technological society.⁵ Thus, while the classroom tools of blackboards and books that shape *how* learning takes place have changed little over the past century, societal demands on *what* students learn have increased dramatically.

There is broad consensus among education policy analysts that satisfying these demands will require rethinking how educators support learning.⁶ Debate now focuses on identifying and implementing the most appropriate and highest priority reforms in the areas of curricula, teacher training, student assessment, administration, buildings, and safety. The role technology could or should play within this reform movement has yet to be defined. Past innovations in media technology, including radio, television, film, and video, have had only isolated, marginal impacts on how and what children learn in school, despite early champions of their revolutionary educational potential.⁷ Similarly, while computer technology is a pervasive and powerful force

in society today with many proponents of its educational benefits, it is also expensive and potentially disruptive or misguided in some of its uses and, in the end, may have only marginal impacts. Nevertheless, several billion in public and private funds have been dedicated to equipping schools with computers and connections to the Internet, and there are promises of even more funds dedicated to this purpose in the future.⁸ (See appendix A in this journal issue for more information on sources of funding.) As ever-increasing resources are committed to bringing computers into the classroom, parents, policymakers, and educators need to be able to determine how technology can be used most effectively to improve student learning.⁹

This article explores the characteristics of computer technology and its potential to enhance learning. The first section highlights a number of computer-based technology applications shown to be effective in improving how and what children learn. Of course, just because computer technology can lead to improvements in learning does not mean that it will do so merely as a result of infusing technology into the classroom. Studies overwhelmingly suggest that computer-based technology is only one element in what must be a coordinated approach to improving curriculum, pedagogy, assessment, teacher development, and other aspects of school structure. Therefore, the second section discusses the changes in organizational structures and supports that should be considered when schools are planning a strategy for incorporating technology. The article concludes with a brief discussion of a framework to guide future research efforts.

Effective Use of Technology as a Learning Tool

Studies conducted on the effectiveness of technology in the classroom often have mixed results, making it difficult to generalize about technology's overall impact in improving

learning.^{10 11} For example, in one of the few large-scale, rigorously controlled studies conducted nationwide, some approaches to using educational technology were found to increase fourth- and eighth-grade students' mathematical understanding, while others proved less effective.¹² More specifically, computer-based applications that encouraged students to reason deeply about mathematics increased learning, while applications that attempted to make repetitive skill practice more entertaining for students actually seemed to decrease performance. In contrast, a meta-analysis of over 500 research studies of computer-based instruction found positive effects on student achievement tests resulted primarily from computer tutoring applications; other uses of the computer, such as simulations and enrichment applications, were found to have only minimal effects. (See table 1 at the end of this article for a summary of findings from these and several other major studies on the effects of technology use in kindergarten through 12th-grade classrooms.)

Three key reasons contribute to these mixed results. First, hardware and software vary among schools, and there is even greater variation in the ways schools use technology, so the failure to produce uniform results is not surprising. Second, successful use of technology is always accompanied by concurrent reforms in other areas such as curriculum, assessment, and teacher professional development, so the gains in learning cannot be attributed to use of technology alone.¹³ And third, rigorously structured longitudinal studies that document the isolated effects of technology are expensive and difficult to implement, so few have been conducted.

While today's research can only support limited conclusions about the overall effectiveness of technology expenditures in improving education, studies conducted to date

suggest that certain computer-based applications can enhance learning for students at various achievement levels. The following sections highlight several promising applications for improving how and what children learn. The “how” and the “what” are separated because not only can technology help children learn things better, it can also help them learn better things. Framed in terms of the growing expectations in mathematics instruction, the “how” addresses the problem of enhancing the learning of the 70% to 100% of students already expected to learn algebra. The “what” addresses the problem of making it possible for the vast majority of students to go beyond algebra to learn calculus—a topic that is unreachable for most students without a revitalized curriculum that takes advantage of technology.

Based on the research to date, the strongest evidence showing positive gains in learning tends to focus on applications in science and mathematics for upper elementary, middle, and high school students, and generally applies to both boys and girls. Future research may find gains that are equally strong for the lower elementary grades and across other curriculum areas, or that are gender or age specific. Meanwhile, the discussion below reflects the limitations of the research to date, and although promising applications across a variety of subjects are considered, applications in the areas of science and mathematics are most often highlighted.

Enhancing How Children Learn

A major scientific accomplishment of the twentieth century has been the great advancements in the understanding of cognition – that is, the mental processes of thinking, perceiving, and remembering.¹⁴ For example, cognitive research has shown that learning is most effective when four fundamental characteristics are present: (1) active engagement, (2) participation in groups, (3) frequent interaction and feedback, and (4) connections to real-world contexts. Interestingly, some of the pioneers in learning research have also been pioneers in

exploring how technologies can improve learning. These connections are not coincidental. As scientists have understood more about the fundamental characteristics of learning, they have realized that the structure and resources of traditional classrooms often provide quite poor support for learning, while technology – when used effectively – can provide ways of teaching that are much better matched to how children learn. The following discussion describes specific computer-based technologies that have been shown to support each of the four fundamental characteristics of learning noted above.

Learning through active engagement

Learning research has shown that students learn best by actively “constructing” knowledge from a combination of experience, interpretation, and structured interactions with peers and teachers.^{14 15} When students are placed in the relatively passive role of receiving information from lectures and texts (the “transmission” model of learning), they often fail to develop sufficient understanding to be able to apply what they have learned to situations outside their texts and classrooms.¹⁶ In addition, children have different learning styles. The use of methods beyond lectures and books can help reach children who learn best from a combination of teaching approaches.¹⁷ Today’s theories of learning differ in some details,¹⁸ but educational reformers appear to agree with the theoreticians and experts that to enhance learning, more attention should be given to actively engaging children in the learning process. Curricular frameworks now expect students to take active roles in solving problems, communicating effectively, analyzing information, and designing solutions – skills that go far beyond the mere recitation of correct responses.¹⁹

While active, constructive learning can be integrated in classrooms with or without the use of computers, the characteristics of computer-based technologies make them a particularly useful tool for this type of learning. For example, consider science laboratory experiments. Certainly students can actively engage in experiments without computers. Yet nearly two decades of research has shown that students can make significant gains when computers are incorporated into labs under a design called “Microcomputer-Based Laboratories” (MBL). As

illustrated by the description of an MBL in Box 1, students conducting experiments can use computers to instantaneously graph their data, thus reducing the time between gathering data and beginning to interpret it. No longer must students go home to laboriously plot points on a graph, and then bring the graphs back to school the following day. Instead, students can instantaneously see the results of their experiment. In fairly widely replicated studies, researchers have noted significant improvements in the graph interpretation skills, understanding of scientific concepts, and motivation of students using the software.²⁰ For example, one study of 125 seventh and eighth graders found that use of MBL software resulted in an 81% gain in the students' ability to interpret and use graphs.²¹ In another study of 249 eighth-graders, experience with MBL was found to produce significant gains in the students' ability to identify some of the reasons why graphs may be inaccurate.²²

[insert Box 1 about here]

The use of technology to engage students more actively in learning is not limited to science and mathematics. For example, computer-based applications such as desktop publishing and desktop video can be used to more actively involve students in constructing presentations that reflect their understanding and knowledge on a variety of subjects. While previous media technologies generally placed children in the role of passive observers, these new technologies make construction of content much more accessible to students, and research indicates such uses of technology can have significant positive effects. In one project, inner-city high school students worked as "multi-media designers" to create an electronic school yearbook and displays for a local children's museum. The students participating in the project experienced significant

gains in measures of task engagement and self-confidence compared to students enrolled in a more traditional computer class.²³

Learning through participation in groups

One influential line of learning research focuses on the social basis for children's learning, inspired by the seminal research of the Russian psychologist Vygotsky.²⁴ Social contexts give students the opportunity to successfully carry out more complex skills than they could execute alone. Performing a task with others not only provides an opportunity to imitate what others are doing, but also to discuss the task and make thinking visible. Much learning is about the meaning and correct usage of ideas, symbols, and representations. Through informal social conversation and gestures, students and teachers can provide explicit advice, clear up misunderstandings, and ensure corrections are made. In addition, social needs often drive a child's reason for learning. Because a child's social identity is enhanced by participating in a community or by becoming a member of a group,²⁵ involving students in a social intellectual activity can be a powerful motivator and can lead to better learning than relying on individual deskwork.

Some critics feel that computer technology encourages asocial and addictive behavior, and taps very little of the social basis of learning. Several computer-based applications, such as tutorials and drill and practice exercises, do engage students individually. At the same time, projects that use computers to facilitate educational collaboration span nearly the entire history of the Internet, dating back to the creation of electronic bulletin boards in the 1970s.²⁶ Some of the most prominent uses of computers today are communications-oriented, and networking technologies such as the Internet and digital video permit a broad new range of collaborative

activities in schools. Use of technology to promote such collaborative activities can enhance the degree to which classrooms are socially active and productive, and can encourage classroom conversations that expand students' understanding of the subject.²⁷

One major, long-term effort that exemplifies many of the promising features of collaborative technology is the Computer-Supported Intentional Learning Environment (CSILE, pronounced “Cecil”).²⁸ The goal of CSILE is to support structured collaborative knowledge building by having students communicate their ideas and criticisms—in the form of questions, statements, and diagrams—to a shared database classified by different types of thinking (see Box 2). By classifying the discussion in this way, students become more aware of how to organize their growing knowledge. In addition, CSILE permits students or experts to participate independent of their physical location. Students can work with other students from their classroom or school, or from around the globe, to build a common understanding of some topic. As illustrated in Figure 1, students in K–12 classes who use CSILE for science, history, and social studies perform better on standardized tests and create deeper explanations than students in classes without this technology.²⁹ Although all students show improvement, positive effects are especially strong for students categorized as low or middle achievers.³⁰

[insert Box 2 about here]

[insert Figure 1 about here]

Many types of learning networks have been created for use in classrooms at all levels. For example, the “AT&T Learning Circles” project uses computer networking to enable multicultural and multilingual collaborative learning, partnering classrooms in different countries to produce newsletters or other writing projects.³¹ The “Multimedia Forum Kiosk” and “SpeakEasy” projects³² structure students’ collaborative interactions, resulting in more inclusive and gender-equitable participation than ordinarily occurs in face-to-face classroom discussions.³³ “ConvinceMe!” and “Belvedere” are both systems that help students to distinguish between hypotheses and evidence, and to produce clearer scientific explanations.³⁴ Reports from researchers and teachers suggest that students who participate in computer-connected learning networks show increased motivation, a deeper understanding of concepts, and an increased willingness to tackle difficult questions.^{31 35}

Learning through frequent interaction and feedback

In traditional classrooms, students typically have very little time to interact with materials, each other, or the teacher.³⁶ Moreover, students must often wait days or weeks after handing in classroom work before receiving feedback. In contrast, research suggests that learning proceeds most rapidly when learners have frequent opportunities to apply the ideas they are learning, and when feedback on the success or failure of an idea comes almost immediately.³⁷

Unlike other media, computer technology supports this learning principle in at least three ways. First, computer tools themselves can encourage rapid interaction and feedback. For example, using interactive graphing, a student may explore the behavior of a mathematical model very rapidly, getting a quicker feel for the range of variation in the model. If the same student graphed each parameter setting for the model by hand, it would take much longer to

explore the range of variation. Second, computer tools can engage students in working for extended periods on their own or in small groups. This can create more time for the teacher to give individual feedback to particular children.³⁸ Third, in some cases, computer tools can be used to analyze each child's performance and provide more timely and targeted feedback than the student typically receives.³⁹

Research indicates that computer applications such as those described above can be very effective tools to support learning.⁴⁰ One study compared two methods of e-mail-based coaching. In the first method, tutors generated a custom response for each student. In the second method, tutors sent the student an appropriate boilerplate response.⁴¹ Students' learning improved significantly and approximately equally in both cases, but the boilerplate-based coaching allowed four times as many students to have access to a tutor.⁴² In another version of computer-assisted feedback, a program called DIAGNOSER assesses students' understanding of physics concepts in situations where students typically make mistakes, then provides teachers with suggested remedial activities (see Box 3).⁴³ Data from experimental and control classrooms showed scores rising over 15% when teachers incorporated use of DIAGNOSER, and the results were equally strong for low, middle, and high achievers.

[insert Box 3 about here]

The most sophisticated applications of computers in this area have tried to trace students' reasoning process step-by-step, and provide tutoring whenever students stray from correct reasoning. Results from "Geometry Tutor," an application which uses this approach, showed much faster learning of geometry, especially for average or lower achievers or students with low

self-confidence in mathematics.⁴⁴ Also, researchers at Carnegie Mellon University found that urban high school students using another application, “Practical Algebra Tutor,” showed small gains on standardized math tests such as the Scholastic Aptitude Test (SAT), but more than doubled their achievement in complex problem solving compared to students not using this technology.⁴⁵

Learning through connections to real-world contexts

One of the core themes of twentieth century learning research has been the frequent failure of students to apply what they learn in school to problems they encounter in the real world. A vast literature on this topic suggests that to develop the ability to transfer knowledge from the classroom to the real world, learners must master underlying concepts, not simply memorize facts and solution techniques in simplified or artificial contexts.¹⁴ But typical problem-solving assignments do not afford students the opportunity to learn when to apply particular ideas, since it is usually obvious that the right ideas to apply are those from the immediately preceding text.

Computer technology can provide students with an excellent tool for applying concepts in a variety of contexts, thereby breaking the artificial isolation of school subject matter from real-world situations. For example, through the communication features of computer-based technology, students have access to the latest scientific data and expeditions, whether from a NASA mission to Mars, an on-going archeological dig in Mexico, or a remotely-controlled telescope in Hawaii. Further, technology can bring unprecedented opportunities for students to actively participate in the kind of experimentation, design, and reflection that professionals routinely do, with access to the same tools professionals use. Through the Internet, students from

around the world can work as partners to scientists, businessmen, and policymakers who are making valued contributions to society.

One important project that allows students to actively participate in a real-world research project is the Global Learning and Observations to Benefit the Environment (GLOBE) program. Begun in 1992 by Vice-President Al Gore as an innovative way to aid the environment and help students learn science, the GLOBE program currently links over 3,800 schools around the world to scientists.⁴⁶ Teachers and students collect local environmental data for use by scientists, and the scientists provide mentoring to the teachers and students about how to apply scientific concepts in analyzing real environmental problems (see Box 4). Thus, the GLOBE Program depends on students to help monitor the environment while also educating them about it. Further, the students are motivated to become more engaged in learning because they are aiding real scientific research, and their data collection has lasting value. In a 1998 survey, 62% of teachers using the GLOBE program reported that they had students analyze, discuss, or interpret the data. While no rigorous evaluations of effects on learning have been conducted, GLOBE teachers who were surveyed said they view the program as very effective, and indicated the greatest student gains occurred in the areas of observational and measurement skills, ability to work in small groups, and technology skills.⁴⁷

[insert Box 4 about here]

Similarly, in the Global Lab Curriculum project, scientists have crafted techniques that allow students around the world to gather and share data about the terrestrial, aquatic, and aerial aspects of their locale.⁴⁸ They study local soil quality, the electrical conductivity and pH of the

rainfall, and ultraviolet radiation, airborne particulates, and carbon dioxide in the air. Results are pooled through telecommunications, and students analyze their data with peers and scientists from around the world. Many other projects also connect teachers and students with scientists to allow active engagement in real-world experiences. For example, the Jason Project, originated by the world-famous explorer Robert Ballard, invites students along on scientific expeditions with “telepresence” connections over the Internet.⁴⁹ In these expeditions, students communicate with scientists who are exploring coral reefs or studying a rain forest. In the KidSat project, students direct the operation of a camera on the NASA Space Shuttle.⁵⁰

Projects have also been developed to connect students with real-world experiences in non-science subject areas. For example, the JASPER Project demonstrated significant improvements in mathematical understanding when teachers used videodiscs of adventure stories that encouraged students to engage in meaningful mathematical problem solving.⁵¹ Researchers assessed Jasper’s effectiveness in 28 middle schools in 9 states. After a month, students using the technology scored about the same on standardized math tests, but showed improvement in their ability to solve complex problems and more positive attitudes towards the role of mathematics in solving real problems, compared to students not using the program (see figure 2).¹⁴

[insert Figure 2 about here]

Expanding What Children Learn

In addition to supporting *how* children learn, computer-based technology can also improve *what* children learn by providing exposure to ideas and experiences that would be inaccessible for

most children any other way. For example, because synthesizers can perform music, students can now experiment with composing music even before they can play an instrument. Because communications technology makes it possible to see and talk to others in different parts of the world, students can learn about archeology by following the progress of a real dig in the jungles of Mexico. Through on-line communications, students can reach beyond their own community to find teachers and other students who share their academic interests.

The most interesting research on the ways technology can improve what children learn, however, focuses on applications that can help students understand core concepts in subjects like science, math, and literacy by representing subject matter in less complicated ways. The research in this area has demonstrated that technology can lead to profound changes in what children learn. By utilizing the computers' capacity for simulation, dynamically linked notations, and interactivity, ordinary students can achieve extraordinary command of sophisticated concepts. Computer-based applications that have had significant impacts on what children learn in the areas of science, mathematics, and the humanities are discussed below.

Science: Visualization, modeling, and simulation

Over the past two decades, researchers have begun to carefully examine what students actually learn in science courses. To their surprise, even high scoring students at prestigious universities show little ability to provide scientific explanations for simple phenomena, such as tossing a ball in the air. This widely replicated research shows that while students may be able to calculate correctly using scientific formulas, they often do not understand the concepts behind the formulas.⁵²

Computer-based applications using visualization, modeling, and simulation have been proven to be very powerful tools for teaching various scientific concepts. The research literature abounds with successful applications that have enabled students to master concepts usually considered too sophisticated for their grade level.⁵³ For example, technology using dynamic diagrams – that is, pictures that can move in response to a range of input – can help students visualize and understand the forces underlying various phenomena. Involving students in making sense of computer simulations that model physical phenomena, but defy intuitive explanations, has also been shown to be a useful technique. One example of this work is ThinkerTools, a simulation program that allows middle school students to visualize the concepts of velocity and acceleration (see Box 5).⁵⁴ In controlled studies, researchers found that middle school students who used ThinkerTools developed the ability to give correct scientific explanations of Newtonian principles several grade levels before the concept is usually taught. Middle school students who participated in ThinkerTools outperformed high school physics students in their ability to apply the basic principles of Newtonian mechanics to real-world situations: the middle schoolers averaged 68% correct answers on a six-item multiple-choice test, compared with 50% for the high school physics students.⁵⁵ Researchers concluded that the use of the ThinkerTools software appeared to make science interesting and accessible to a wider range of students than was possible with more traditional approaches.

[insert Box 5 about here]

Other software applications have been proven successful in helping students master advanced concepts underlying a variety of phenomena. The application “Stella” enables high school students to learn system dynamics—the modeling of economic, social, and physical

situations using a set of interacting equations—which is ordinarily an advanced undergraduate course.⁵⁶ Another software application uses special versions of “Logo,” a programming language designed especially for children, to help high school students learn the concepts that govern bird flocking and highway traffic patterns, even though the mathematics needed to understand these concepts is not ordinarily taught until graduate level studies.⁵⁷ And yet another application, the “Global Exchange” curricula, reaches tens of thousands of pre-college students annually with weather map visualizations that enable school children to reason like meteorologists. Research has shown that students using the curricula demonstrate increases in both their comprehension of meteorology and their skill in scientific inquiry.⁵⁸

Mathematics: Dynamic, linked notations

As suggested above, the central challenge of mathematics education is teaching sophisticated concepts to a much broader population than has traditionally been taught such material. This challenge is not unique to the United States – almost every nation is disappointed with the mathematical capabilities of their students.⁵⁹ Not so long ago, simple merchant mathematics (addition, subtraction, multiplication, and division) sufficed for almost everyone, but in today’s society, individuals are increasingly called upon to use mathematical skills to reason about uncertainty, change, trends in data, and spatial relations.

While seeking techniques for increasing how much mathematics students can learn, researchers have found that the move from traditional paper-based mathematical notations (such as algebraic symbols) to on-screen notations (including algebraic symbols, but also graphs, tables, and geometric figures) can have a dramatic effect. In comparison to the use of paper and

pencil which supports only static, isolated notations, use of computers allows for “dynamic, linked notations” with several helpful advantages, as described below:⁶⁰

- Students can rapidly explore changes in the notation by dragging with a mouse, as opposed to slowly and painstakingly rewriting the changes.
- Students can see the effects of changing one notation upon another, such as modifying the value of a parameter of an equation and seeing how the resulting graph changes its shape.
- Students can easily relate mathematical symbols either to data from the real world or to simulations of familiar phenomena, giving the mathematics a greater sense of meaning.
- Students can receive feedback when they create a notation that is incorrect. (For example, unlike with paper and pencil, a computer can beep if a student tries to sketch a nonsensical mathematical function in a graph, such as one that “loops back” to define two different y values for the same x value.)

Using dynamic, linked notations, the SimCalc Project has shown that middle school students in some of the most challenging urban settings can learn calculus concepts such as rate, accumulation, limit, and mean value using computers (see Box 6).⁶¹ Studies across several different SimCalc field sites found that inner-city middle school students—many of whom ordinarily would be weeded out of mathematics before reaching this level—were able to surpass the efforts of college students in their understanding of fundamental concepts of calculus, based on the SimCalc assessment which stressed conceptual understanding of calculus, not symbolic computation. Results of the assessment showed that through exposure to SimCalc, inner-city middle school students increased their percentage of correct responses from only 10–20% to 90–100% in a few months, while only 30% to 40% of college-level students answered correctly

to some of these same items. According to researchers, the capacity of computers to enable students to reason while directly editing dynamic graphs and related notations is the central innovation responsible for this breakthrough.

[insert Box 6 about here]

Another example of a software application using screen-based notations is Geometer's Sketchpad, a tool for directly exploring geometric constructions on screen. Such applications are revitalizing the teaching of geometry to high school students, and in a few instances, students have even been able to contribute novel and elegant proofs to the professional mathematical literature.⁶² Graphing calculators, which are reaching millions of new high school and middle school students each year, are less sophisticated than some of the desktop computer-based technologies, but they can display algebra, graphs and tables, and can show how each of these notations represents the same mathematical object.⁶³ Through the use of such tools, screen-based notations are enabling an expansion of mathematical literacy in a growing number of our nation's classrooms.

Social studies, language, and the arts

Unlike science and math, breakthrough uses of technology in other subject areas have yet to crystallize into easily identified types of applications. Nonetheless, innovators have shown that similar learning breakthroughs in these areas are possible. For example, the commercially successful SimCity game (which is more an interactive simulation than a traditional video game) has been used to teach students about urban planning. Computer-based tools have been designed to allow students to choreograph a scene in a Shakespeare play,⁶⁴ or to explore classic movies,

such as *Citizen Kane*, from multiple points of view to increase their ability to consider alternative literary interpretations.⁶⁵ Through the “Perseus Project,” students are provided access to a pioneering multimedia learning environment for exploring hyperlinked documents and cultural artifacts from ancient civilization.⁶⁶ Similar software can provide interactive media environments for classes in the arts. An emergent theme in many computer-based applications in the humanities is the use of technology to allow students to engage in an element of design, complementing and enhancing the traditional emphasis on appreciation.

While there are fewer studies on the effectiveness of the use of technology in these other subject areas, one recent study documented the experience of two sixth grade classes participating in a social studies project on the Spanish colonization of Latin America. The study found that the students who used computers to create a multimedia presentation on what they had learned scored significantly higher on a post-test, compared with members of the other sixth-grade class that completed a textbook-based unit on the same topic.⁶⁷ Another study examined the effectiveness of using interactive storybooks to develop basic language skills and found that first graders using the technology-based system demonstrated significantly greater gains compared to those receiving only traditional instruction.⁶⁸

In one innovative project, elementary and middle school children alternate between playing musical instruments, singing, and programming music on the computer using “Tuneblocks,” a musical version of the Logo programming language.⁶⁹ A variety of compelling case studies show how using this software enables ordinary children to learn abstract musical concepts like phrase, figure, and meter—concepts normally taught in college music theory classes. In another example, a tool called Hypergami has been developed that enables art

students to plan complicated mathematical sculptures in paper.⁷⁰ Experiences with Hypergami have been shown to produce significant gains in boys' and girls' performance on the spatial reasoning sections of the SAT.⁷¹

The Challenges of Implementation

The preceding overview provides only a small glimpse of the many computer-based applications that can enhance learning. But simply installing computers and Internet access in schools will not be sufficient to replicate these examples for large numbers of learners. Models of successful technology use combine the introduction of computer tools with new instructional approaches and new organizational structures. This is because the American educational system is somewhat like an interlocking jigsaw puzzle.⁷² Efforts to change one piece of the puzzle—such as by using technology to support a different kind of content and instructional approach—are more likely to be successful if the surrounding pieces of teacher development, curriculum, assessment, and the school's capacity for reform are changed as well. Each of these organizational change factors is examined briefly below.

Teacher Support

Effective use of computers in the classroom requires increased opportunities for teachers to learn how to make use of the technology. Studies show that a teacher's ability to help students depends greatly on a mastery of the structure of the knowledge in the domain to be taught.⁷³ Teaching with technology is no different in this regard. Numerous surveys of the literature link student achievement using technology to the extent to which teachers have the opportunity to develop their own computer skills.⁷⁴ Yet teachers are commonly required to devote almost all of

their time to solo preparation and performance, with little time available for training in the use of technology.⁷⁵

Technology itself, however, is proving to be a powerful tool in helping teachers bridge the gap in training on effective use of computers.¹⁴ By networking with other teachers and with mentors electronically, teachers can overcome the isolation of the classroom, share insights and resources, support one another's efforts, and engage in collaborative projects with similarly motivated teachers. Teachers are also gain valuable experience by using computers for their own needs.

Teachers who succeed in using technology often make substantial changes in their teaching style and in the curriculum they use. However, making such changes is difficult without appropriate support and commitment from school administration, as discussed below.

Curriculum Modernization

The type of curriculum adopted by a school has a significant impact in determining the extent to which computer-based technologies can be integrated effectively into the classroom. On the one hand, many parents and educators believe that students should master basic skills before they are exposed to challenging content, and computer technology can be used to support a curriculum with this emphasis through drill and practice applications. On the other hand, many learning researchers argue that the most effective way of promoting learning is to embed basic skills instruction within more complex tasks. They advocate adopting a curriculum that teaches the higher-order skills of reasoning, comprehension, and design in tandem with the basic skills of computation, word decoding, and language mechanics.⁷⁶ Because computer technology has been

shown to be most effective when used to support the learning of these more complex skills and concepts, computer-based technology can be integrated most effectively into a curriculum that embraces this tandem approach.

National associations and research institutions have called for challenging content to prepare students for the twenty-first century.⁷⁷ To date, some progress has been made in setting more challenging goals in national standards and state curriculum framework documents, especially in the areas of science and mathematics. The National Council of Teachers of Mathematics K-12 standards are often cited as an example of a sensible and widely implemented set of goals,⁷⁸ and many experiments with technology are now oriented toward helping meet these standards. Progress has also been made in setting more challenging goals for science learning,⁷⁹ while less progress has been made in updating goals in other subject areas. Strategies for effective, broad-scale adoption of particular technologies are dependent upon progress in the adoption of more challenging national and statewide goals by community stakeholders, including teachers, parents, school boards and administrators.

Student Assessment and Evaluation

One of the biggest barriers to the introduction of effective technology applications in classrooms is the heavy focus on student performance on district or state-mandated assessments, and the mismatch between the content of those assessments and the kinds of higher-order learning supported most effectively by technology.⁸⁰ This mismatch leads to less time available for higher-order instruction, and less appreciation of the impact technology can have on learning. Time spent preparing students to do well on tests of numerical calculations, vocabulary, or English mechanics, cannot be spent on learning about acceleration, the mathematics of change,

or the structure of Shakespeare's plays. Moreover, it will be difficult, if not impossible, to demonstrate the contribution of technologies in developing students' abilities to reason and understand concepts in-depth without new kinds of assessments. As noted earlier, compared with peers who learned algebra through conventional methods, urban high school students who used a computer-based algebra tutor system did much better on tests that stress their ability to think creatively about a complex problem over a longer time period, but showed only a small advantage on standardized tests which do not adequately measure such higher-order thinking skills.^{45 81} While it is challenging to develop ways to measure student understanding of complex concepts and higher-order thinking skills, current research on the effectiveness of selected computer-based applications may provide strategies that could be considered for adoption in future educational assessment frameworks.⁸²

Capacity for Change

Systematic studies of schools that have implemented educational reforms provide useful information about the organizational dynamics of significant change and the role computer technology can play in this process. In a series of cross-sectional case studies conducted in 1995, several key factors associated with effective use of technology in schools were identified:⁸³

- technology access and technical support;
- instructional vision, and a rationale linking the vision to technology use;
- a critical mass of teachers in technology activities;
- a high degree of collaboration among teachers;
- strong leaders; and
- support for teacher time for planning, collaboration, and reporting technology use.

These findings were echoed more recently in a 1998 survey of over 4,000 teachers which identified the following key factors affecting school computer use: location and number of computers available to a class; teacher computer expertise; teacher philosophy and objectives; and school culture (see article by Becker in this journal issue). Specifically, this survey found that Internet use is more common in schools where teachers talk to their colleagues and have the opportunity to visit each other's classrooms.⁸⁴ In fact, such teacher-to-teacher interaction was more strongly associated with Internet use than participation in training on how to use the Internet. These studies suggest that the relationship between technology use and education reform is reciprocal: while technology use helps support school change, school change efforts also help support effective use of technology.⁸⁵

Conclusions and Policy Implications

Using technology to improve education is not a simple matter. There are many kinds of technology, and many ways that an attempted use can fail. From a policy perspective, it would be desirable to have clear and broadly generalizable measures of effectiveness before committing to continual investments in technology. Such data might take the form "for every x% of a school budget re-allocated to technology, student learning will improve by y%." Unfortunately, the existing research falls short of providing such clear measures of effectiveness. Even so, many policymakers, parents, and educators are rapidly moving ahead to introduce computers into the classroom. The challenge is to ensure this technology is used effectively to enhance how and what children learn.

To help inform future decisions about ways to improve how and what students learn, further explorations of effective use of technology are needed. The continuum of explorations for educational improvement stretches from basic research on learning with technology, to applied research looking at the classroom practicalities of improving teaching when technology is a component. These explorations, whether carried out by schools, individual teachers, university researchers, or others, should be executed with a reflective, research component so that the knowledge gained can add to the rational basis used for making effective decisions. Four factors, sometimes referred to as the “four C’s,” can be used to guide these future explorations:

1. **Cognitive learning.** Much more is currently known about how children learn than was known a century ago. Technology applications selected for future research should engage the cognitive characteristics of learning as a constructive, collaborative, interactive, contextualized process.
2. **Curricular reforms.** Given societal pressure for individuals to know more than ever before, it is particularly important to explore technology that is adopted in tandem with curricular reforms that make complex subject matter accessible to a higher percentage of children.
3. **Coordinated interventions.** Successful implementation of technology requires a context of coordinated interventions to improve curricula, assessment, teacher development, and all the other pieces of the education jigsaw puzzle. Explorations of technology implementations should focus on schools that are striving to have all these pieces of the puzzle in place.

4. **Capacity for change.** Today's schools are not all equally well-prepared to accept technology and use it to achieve improvements in student learning. For improvements that include technology to take hold, schools need to develop their capacity for change with appropriate resources and processes that enable all the involved parties to manage the challenging transition. Thus, effective uses of technology should be explored in schools that are well-prepared for change.

To maximize the effectiveness of computer technology as a tool to enhance learning in the classroom, education policymakers must incorporate technology selectively into educational reform as part of an overall program for improvement, and continue to study its progress and results to improve efforts over time. Using the "four C" framework outlined above, future research can help target initial applications of technology that are most likely to improve learning within overall programs of experimental reform.

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