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Chapter 5

Technology's Contribution to Teaching and Policy: Efficiency, Standardization, or Transformation?

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The dramatic influx of technology into America's schools since the 1990s prompts the question of technology's role as a lever for policy. We begin this chapter with a brief sketch of alternative perspectives on the ways in which technology can support education policy and practice. We will suggest that the connection between technology and policy is looser than that between policy and the other mechanisms described in this volume (such as standards or state assessments) and that technology's potential for profound influences on instruction is yet to be realized.

After the introduction to alternative ways in which policymakers have viewed technology's role, we focus on emerging areas of classroom use of technology where prospects for significant changes in teaching and learning seem strongest. Our selection of particular technology uses for more extended treatment reflects our choice of teaching and learning at the classroom level as our central focus.¹ In an education system as decentralized as that of the United States, teachers have considerable latitude—even in these days of increased accountability—in interpreting and implementing policies developed at higher levels of the education system.

The view of instruction underlying our thinking concerning the policy-technology connection is congruent with Cohen and Ball's (1999) description of instructional capacity as the product of complex interactions among teachers, students, and instructional content. In this view, instructional materials or regimens are not fixed entities with entirely predictable effects. Rather, "teachers mediate instruction: their interpretation of educational materials affects curriculum potential and use, and their understanding of students affects students' opportunities to learn" (p. 4). Students, in turn, respond to teachers and materials in ways that influence subsequent teacher actions. Cohen and Ball caution policymakers against assuming that addressing a single aspect of this complex system (even an aspect that is as strong a policy driver as curriculum materials or assessments) can in fact have the intended effect on the system as a whole.

BACKGROUND

Before honing in on the link between technology and instruction, we review briefly the broader range of education policies with respect to technology use in K–12 education. The rapid spread of computer technology and Internet access across the K–12 system has been well documented. In 2002, for example, 92% of instructional classrooms in K–12 public schools had Internet access (National Center for Education Statistics, 2003). The spread of computer and network technology has supported states and school districts in applying the policy levers discussed in other chapters in this volume: Technologies have supported system-wide professional development, disseminated standards-based curricula and assessments, and, in a few cases, delivered wide-scale assessments. Technology is also being used by school districts to facilitate communications and operations, for example, by communicating school events, policies, and homework assignments to parents and students; archiving lesson plans in a standard format; automating records of grades and attendance; giving parents access to their children's course assignment grades and attendance; and giving school staff access to student data (especially standardized test data) maintained at the district level. In addition, some districts and schools are actively engaged in efforts to use technology to improve instruction or catalyze an education reform agenda (Allen, 2003; Stapleton, *in press*).

In considering the many educational uses of technology and how technology has been and could be used as a policy tool, we have found it helpful to develop categories of use, as follows²: (a) topic for instruction, (b) system for automating school and classroom management practices, (c) curriculum resource, and (d) tool for informing instructional practice. We briefly review each of these categories before honing in on emerging trends and potential innovations falling under the fourth use category—an area where we see the fewest current examples of technology supports but where some researchers and practitioners have begun to explore the potential for transforming teaching and learning.

TECHNOLOGY AS A TOPIC FOR INSTRUCTION

One of the first ways in which the education policy community engaged with technology was to advocate technology “proficiency,” “literacy,” or “fluency” for students. This stance toward technology in schools treats the technology as an end in itself. To fulfill technology educational objectives, schools provide students with practice using computers and software so that they can attain the desired technology capabilities. In the early 1980s, school uses of technology emphasized computer programming and computer literacy (Becker, 1985; Kemeny & Kurtz, 1968). However, students in more affluent schools were more likely to be encouraged to learn how to program computers, while those in less well-to-do communities were more likely to use educational software to enhance their basic skills (Becker & Sterling, 1987).

However, as more and more powerful software programs designed for users without facility in the underlying computer language became available, the early emphasis on

teaching computer programming waned (Becker, 1990; Office of Technology Assessment, 1988). The emphasis shifted to ensuring that students became intelligent users of the most widely used software applications: word processors, spreadsheets, search engines, presentation programs, and Web page development tools. This emphasis has been maintained, with increasing numbers of states establishing standards for student and teacher technology proficiency. In 2003, 41 states had explicit student technology proficiency standards, and 40 had standards for teacher proficiency (Ansell & Park, 2003). A small but growing set of states have developed assessments of student and teacher technology proficiency (Crawford & Toyama, 2001). Some states view the creation of a technologically sophisticated set of graduates as part of their economic development strategy. At the federal level, the goal of having every American eighth grader technologically proficient is incorporated into the federal No Child Left Behind (NCLB) legislation.

Such policies typically prompt schools to provide keyboarding and software use practice, often in computer labs rather than regular classrooms. We have reasoned elsewhere that these practices are not sufficient to realize the full potential of technology for improving learning because they do not lead to improvements in the disciplinary content and strategies that are at the heart of the K–12 curriculum (Means, 2000). This is not to say that a school system cannot do both (teach technology skills and use technology to support learning in core content areas) but simply to argue that using technology to promote learning in core content areas requires more than a policy focused on increasing technology proficiency *per se*.

TECHNOLOGY FOR AUTOMATING SCHOOL AND CLASSROOM MANAGEMENT

Educators also look to networks and software systems to provide greater efficiency and better articulation among district, school, and classroom systems in executing education management functions. Software for budget management, grading, and attendance reporting has become increasingly common.

Technologies may serve as policy levers for management in that district policies with respect to these functions can be embodied in software and in effect enforced by technology—for example, when principals need to use certain software templates for submitting their school budgets, attendance records, or the number of their students who qualify for reduced-price or free lunch. Recently, industry has sought to develop standards to make exchange of student record data among different school systems much easier (see <http://www.sifinfo.org>), which should enable more effective implementation of these capabilities. Such arrangements can offer school systems functionality and efficiencies similar to those provided in the business sector, but they do not have a direct impact on the quality of the instruction experienced by students.

TECHNOLOGY AS A CURRICULUM RESOURCE

In contrast to the preceding views of technology as an end in itself or as a means of gaining standardization and efficiency in operations, some policymakers have focused

on technology's potential as the conduit for high-quality, advanced, or required curriculum content. The rapid spread of Internet connectivity and the World Wide Web has led district, state, and federal policymakers to develop technology-supported strategies for disseminating curriculum objectives and materials. The "systemic reform" perspective, with its emphasis on having the multiple parts of the education system reinforce each other (Smith & O'Day, 1990), makes technology-based systems attractive as policy levers because the systems can support users in moving from standards to objectives and materials to assessments and back again (Quellmalz, 1999). This use of technology appears to have received a major impetus from the standards-based reform movement generally and especially from the accountability focus of NCLB. The notion of technology as the conduit for better curriculum is not new, however; this strategy dates back more than 50 years.

Early computer-assisted instruction (CAI), derived from Skinnerian learning theory, was developed with the belief that technology could provide better learning experiences than a human teacher (Means et al., 1993). Technology pioneers were sometimes explicit in their view that technology, with all its efficiency and an "optimum learning design" created by "experts," would replace human teachers (Pressler & Scheines, 1988). Wholesale replacement of teachers has not occurred, of course, and is not a vision embraced by many policymakers today, nor by many technologists or curriculum developers (Culp, Hawkins, & Honey, 1999; Pea, Wulf, Elliott, & Darling, 2003).

CAI has found a niche in schools, though, particularly in the area of basic skills practice (Cohen, 1988; Newman, 1990). Newer CAI software features more bells and whistles, in the form of more sophisticated user interfaces, multimedia, and instructional management capabilities (see for example, Pearson's *KnowledgeBox* or AutoSkill's *Academy of Reading*), as well as, in some cases, artificial intelligence. An early example of *intelligent* CAI is the *GeometryTutor* developed at Carnegie-Mellon University (Anderson, Boyle, & Yost, 1985; Schofield, Evans-Rhodes, & Huber, 1989), which allows students to prove conjectures; a more recent example is found in cognitive tutors, such as the *PUMP AlgebraTutor* (Anderson, Corbett, Koedinger, & Pelletier, 1995).

Although dismantling of face-to-face instruction in K–12 education seems unlikely, we are seeing a trend toward increasing use of curriculum content made available through the World Wide Web. During the Web's first decade, much of this content was provided by universities, museums, nonprofit organizations, and other institutions outside the official K–12 education system. The Web allowed teachers to turn to a much wider array of resources in planning their classroom activities than just the state- and district-approved textbook and teacher's guide. More than 25,000 teachers, for example, have participated in educational activities provided by the JASON Foundation, beginning with the JASON Project, which gave students the opportunity to participate in scientific expeditions with explorer Robert Ballard through "telepresence" connections over the Internet (Ba & Anderson, 2002). Often, the early technology-based learning material developed outside the education system addressed material that

was motivating for many students but far from central to the curriculum (Cohen, 1988; Levin & Meister, 1985).

Increasingly, though, states and districts have harnessed technology in the service of promoting mandated or recommended curricula. Supporting this trend, commercial entities are offering products that districts and states can use to provide schools and teachers with curriculum materials linked to their specific content and proficiency standards. A district can use these products to provide all of its teachers with Web-accessible lessons and assessments geared to local standards. Such products are often promoted as helping districts meet accountability requirements. For example, *Class Server* is described on the Microsoft education Web site as “designed specifically to help educators address the challenges of meeting No Child Left Behind (NCLB) requirements.”

Another technology product marketed as a tool for policymakers is Scholastic's *iReAch*, which provides access to children's books and related assessments that have been linked to standards. A feature of *iReAch* given prominence in product marketing is its ability to generate estimates of how well the students using the *iReAch* reading materials and assessments would do on high-stakes standardized tests. In a similar vein, Lightspan's *eduTest* offers online assessments linked to state standards for classroom use. A selling point for this kind of product is that it enables a principal or district administrator to obtain midyear information on how well students are doing with respect to the requirements for annual improvement in the state's standards for NCLB. (Thus, in an ironic twist, instead of using standardized tests to tell us how much students have learned through instruction, policymakers are encouraged to use how much students have learned through the instruction managed by these systems to predict how well they will do on the state tests.)

In marketing these products to districts, vendors appeal to the desire of policymakers at higher levels of the education system to shape classroom teaching practice. The concerns raised about accountability systems narrowing curriculum coverage and promoting teaching to the test (Confrey & Makar, in press; Shepard, 2000) are relevant here. At the same time, note that technology-based repositories of standards-linked curriculum resources per se cannot *enforce* curriculum mandates; that function is left to policymakers and ultimately, as noted by Cohen and Ball (1999), the teachers responsible for implementing policies. However, the technology does provide a flexible, easily modified set of resources that can be quickly disseminated throughout a system and that can, if well implemented, support instructional goals set by the district or state.

Another prominent example of higher levels of the education system using technology to promote K–12 curriculum content is the burgeoning of distance learning courses and programs, especially at higher grade levels. A recent survey of state education departments showed that 16 states have established statewide “virtual” schools, and 24 states have laws that permit granting charters to schools offering their instruction via the Internet (Ansell & Park, 2003). When sponsored by a state or district education agency, online courses can provide mandated or recommended curricula to

students in schools throughout the jurisdiction, including those in areas without qualified teachers in some of the state-mandated curriculum areas. Similarly, an increasing number of states and districts are experimenting with online professional development activities and networks for teachers (Dede & Nelson, in press; Greene, Durland, & Sloane, 2001).

While policymakers have tended to see technology as a way to deliver curriculum materials that are aligned with standards, a significant portion of the education technology research community has focused on technology's potential for *transforming* what and how students learn (Pea et al., 2003). These developers seek to exploit the affordances of technology—particularly the capability of visually portraying abstract concepts through dynamic graphics and of providing opportunities to construct and interact with models of complex systems—to teach challenging content to a broader group of students and at earlier ages than is the case in the conventional curriculum. *SimCalc*, for example, uses linked dynamic animations, graphs, and equations to provide middle school students with experience in exploring some of the fundamental concepts of calculus (Kaput & Roschelle, 1998). In one study, urban middle school students who worked with *SimCalc* acquired a sufficiently deep knowledge of these concepts to outscore college students on a calculus test (Roschelle & Kaput, 1996).

GenScope is a “computer-based manipulative” that exemplifies a number of modeling tools that allow students to explore scientific and mathematical concepts. (GenScope has been subsumed by a more comprehensive system called *BioLogica*, as described at <http://www.concord.org>.) Students explore scientific and mathematical concepts of genetics through direct manipulation of software that embodies Mendelian genetics (Hickey, Kindfield, Christie, & Horwitz, 1999; Horwitz, Neumann, & Schwartz, 1996). GenScope provides an integrated and systemic view of genetics, focusing on implementing the links between separate levels (DNA, chromosomes, cells, organisms, pedigrees, and populations) while allowing manipulations at each of these levels. Students are able to explore the relation between actions at one level and their effects at higher levels—for example, changes in genes and their effects among individuals and populations.

These technology-supported curriculum research and development efforts attempt to deal with central aspects of the content disciplines (such as *SimCalc*'s treatment of the mathematics of change and GenScope's linking of multiple levels in genetics). At the same time, the learning technology research community seeks to take a long view—dealing with content, such as chaos theory, fractal geometry, and, more recently, nanotechnology, that has recently become important in the practice of a discipline but has not had time to work its way into national and state curriculum standards. Thus, technology can serve policymakers' desire for greater standardization of curriculum coverage, as described earlier, but it can also be part of efforts to significantly transform curricula in response to advances in substantive areas (Pea & Lazowska, 2003) and new views of human cognition (Bransford, Brown, & Cocking, 2000).

The use of interactive and manipulative tools such as *SimCalc* and *GenScope* illustrates an advantage of technology as a curriculum resource: Many of the concepts and

functionalities that the tools enable are constant across disciplines and bring mathematics to bear on science in supportive ways. Well used, technology can provide a curriculum with a sense of constructive continuity.

Some policymakers have promoted laptop devices, and more recently handheld computers, as a way to provide access to such technology supports across the curriculum. Maine's program of providing a laptop computer to every seventh and eighth grader (Lemke, 2003; Silvernail & Harris, 2003) is one of the best-known examples of this strategy. Laptops solve one part of the access problem in providing mobility, but they remain expensive, complex, and all too breakable. Handhelds, like graphing calculators, are low cost, simple, and reliable but have limited screen space and can support fewer functions. Increasingly, however, handhelds can incorporate more of the features of more general computers: In addition to graphing and manipulating mathematics, handhelds now have word processors, concept mapping tools, spreadsheets, data gathering tools, and so forth.³

Eventually, we expect some convergence between the trends: Handhelds will add Internet access, and Internet resources will become tuned for mobile devices. In the short term, however, educators have no single class of technology that is simultaneously extremely affordable (for equity) and very powerful (for excellence). Any given technology can support learning only to the degree that it is available for frequent, integral use within and outside schools. Many researchers see the trend toward more "ubiquitous" technologies such as the Internet and portable handhelds as meeting this challenge. Policymakers could amplify the potential for widespread benefits from technology by helping educators push for more affordable, reliable, readily accessible, and capable product offerings.

TECHNOLOGY FOR INFORMING INSTRUCTIONAL PRACTICE

To really improve education, policies need to affect the teaching and learning that takes place in classrooms. One way to directly affect classroom practice is through provision of curriculum resources, as discussed earlier. Another approach is to change the nature of instructional activities or processes themselves. In the remainder of this chapter, we review some of the newer and less well-known uses of technology intended to improve the process of instruction within classrooms, specifically tools that enhance the teacher's ability to assess students' understanding. We begin with a class of tools for analyzing data on student achievement to support data-driven decision making and then proceed to discuss technologies designed to support teachers' diagnosis of their students' skills and understanding in order to inform instructional decisions at the classroom level.

Student Data Analysis Tools

An example of an increasingly popular use of technology to provide more information to teachers is the growing array of software tools designed to help school staff

analyze student data. In most cases, the data are taken from district- or state-level databases, and the bulk of this information consists of standardized test scores. These systems allow the user to subset the data by according to student characteristics such as grade, class, or ethnicity. The concept behind the systems is that school personnel will have access to the data on their students, and, through exploration and manipulation of those data, they will gain insights into the school's strengths and weaknesses (e.g., "Our fourth graders are doing well in reading, but in math they're behind those in other schools serving similar populations in our district") and provide insights that may lead to closing of achievement gaps for different student groups (e.g., "We aren't obtaining the expected growth in reading comprehension for our students who qualify for free- or reduced-price lunch"). School systems are interested in purchasing such products for their schools (and, in fact, some have developed their own in-house systems) in the hopes that the software will promote reflection and "data-driven decision making." Passage of the NCLB legislation, with its requirement for adequate yearly progress of various student subgroups, has given a federal impetus to this trend (see Stringfield, Waymon, & Yakimowski, *in press*, for a description and discussion of 11 commercially available tools for analyzing student data).

These systems are largely new, and there is universal agreement that school staff need training and support (e.g., in interpreting statistics and basing decisions on data) to use them well. Thus far, we have seen only a few studies on how these systems are implemented (Herman & Gribbons, 2001; Mitchell & Lee, 2000), let alone their impact on student achievement, a deficit that is not surprising given the recency of their availability.

Such systems can support data explorations that could highlight inequities and thereby galvanize school staff for action. The kinds of data they employ can support decisions concerning student placement in particular classes or learning activities with an eye toward equity issues. However, two concerns with respect to these systems have been expressed in the research literature. First, given correlations between student demographic characteristics and scores on standardized tests, there is the potential for the data analysis tool to reinforce stereotypes and the tendency to view the locus of the problem as being the students rather than the educational system or the pedagogy employed. Second, the lack of familiarity with the statistical concepts of measurement error, reliability, and variance on the part of many teachers and school administrators raises concerns about the potential for decision making based on data misinterpretation (see Confrey & Makar, *in press*).

Although not obviating the need for increasing school staff understanding of statistical concepts, we would argue that teachers will be more motivated to undertake data-driven decision making and are likely to do a better job of it if the "data" they are working with consist of information that they collect themselves and that thus is directly relevant to instruction in their classrooms (Guskey, 2003). Some of the student data analysis tools can, in principle at least, be used with data teachers have collected in their own classrooms. In practice, such uses appear rare, however, and decisions to purchase this kind of software appear to be made at higher levels of the

education system (i.e., districts or states) with the goal of promoting the use of standardized test data in decisions made at the school and classroom levels.

Classroom Assessment Tools: Assessments of Individual Students

A contrast to the systems supporting the exploration of standardized test performance data is provided by a set of technologies that support teachers' diagnosis of their students' current level of functioning. A number of companies have large item banks and software that teachers can use to create tests or quizzes for computer-based delivery. (Note that these systems assume that teachers have a curriculum and instructional resources and want to build assessments to match them. Other systems offer preset assessments and linked instructional resources on the assumption that the teacher will use them to shape instruction to match the content covered in the tests.) Some of the technology-based assessment systems can provide students with prompt feedback on the correctness of individual answers and on the percentage of items they answered correctly. These systems may or may not improve the quality of classroom assessments, but in any event they offer the potential efficiencies of faster feedback to the students taking the assessment and reductions in teachers' record-keeping requirements (thus overlapping with the classroom management uses of technology described earlier).

Some commercial systems combine classroom assessment resources with student data analysis tools. An October 2003 press release from CTB/McGraw-Hill, for example, announced an enhancement of the company's *i-know*TM Web-based classroom assessment system to incorporate the ability to link classroom assessment results with district student and teacher data. According to the company, this product provides teachers with the capability to administer assessments in their classrooms and then view their classroom's assessment results in comparison with other classrooms and schools, to disaggregate their data by demographic subgroup, and to use links to instructional resources in planning instruction.

Another recent commercial trend is the development and promotion of systems for supporting classroom assessment with palmtop computers. For example, both Kaplan and Scantron offer item banks that teachers can use to produce tests that students can take on handheld computers. Wireless Generation offers a computerized version of reading records for handhelds.

Ongoing research at the University of Texas Health Science Center at Houston is examining the added value of using handheld computers in implementing systematic classroom assessment practices in early reading. A heavily researched diagnostic tool for early reading, the Texas Primary Reading Inventory (TPRI), is being administered to students by teachers using either the paper-and-pencil records employed in the past or software developed to run on palmtop computers (an application of Wireless Generation's *mClass*). In a pilot test of the software and associated Web-based resources for teachers using the TPRI, the computer-based version of the assessment cut the time required for administration, reduced administration errors (by automating both branching during assessment administration and computation of fluency), and helped

teachers move quickly to the appropriate portion of the assessment when doing mid- and end-of-year testing (B. Foorman, personal communication, October 2003). In an ongoing experimental test of the value of the computer-based version of the TPRI and associated instructional resources and mentoring available through the World Wide Web, teachers in 250 urban and rural schools across Texas have been assigned at random to use either paper records or the software, and differences in student reading achievement are being studied (Foorman, Santi, Mouzaki, & Berger, 2003).

Employing technology to deliver and record findings of the TPRI is useful because of the availability of multiple, research-based instructional regimens (for example, specific instructional strategies and exercises for students who have not yet demonstrated graphophonemic knowledge or phonemic awareness) that can be prescribed for individual students, depending on their performance on the assessment. Both this application and the data-driven decision-making tools described earlier are based on the premise that a classroom's performance can be optimized by differentiated instruction, matching each student with the right regimen. The effectiveness of automated assessment systems for classroom use is likely to depend on the degree of congruence between the content of the assessments and the learning objectives and instructional practices of the classroom. Policymakers need to understand that technology-based assessment systems alone are insufficient to produce desired improvements in student learning.

For the most part, the commercial systems using technology to tailor, deliver, and score assessments for classroom use seek to make standardized tests a part of day-to-day classroom experience. Vendors suggest that students may take a "mini" test in selected skill or content areas as often as twice a week, with the argument that such "formative assessment" will provide teachers with the information they need to focus individual students' instruction on areas of weakness. In effect, this is a mastery learning approach with subtests of standardized achievement tests as the basis for determining learner levels. Although described in marketing material as "formative assessment," this practice is not the same as the diagnostic formative assessment recommended by learning researchers (see, for example, the National Research Council volume *Knowing What Students Know* [Pellegrino, Chudowsky, & Glaser, 2001]).

Learning researchers stress the importance of not only ascertaining that a student has yet to master a particular skill or piece of knowledge but determining the nature of the misconception or partially developed skill the student does have. By understanding the nature of students' thinking, teachers can respond with counterexamples and experiences designed to promote advances from the misconception in question. For example, Hunt and Minstrell (1994) used a detailed analysis of the physics of motion to develop assessment items for which alternative responses are generated on the basis of different "facets" of understanding. Across different items in the assessment, students may demonstrate either a scientific (Newtonian) or a commonsense (Aristotelian) understanding of force and motion. Using these assessments, DIAGNOSER software gives the instructor a diagnosis of the particular facets of knowledge a student possesses—not just the fact that the student is in the x th percentile in terms of mastery

of Newtonian principles. Phil Sadler (1998) has used a similar approach in developing assessments of students' understanding of the solar system in such a way that different patterns of responses differentiate among alternative, common erroneous models of the universe.

Such assessments *for* learning are developed quite differently from standardized tests, which are used as assessments *of* learning (Pellegrino et al., 2001). Assessments of learning are composed of samples of items drawn from a broad universe of potential knowledge or skill components in order to ascertain an examinee's rank order with respect to a national sample of test takers. No matter how important its content, an item that almost everyone answers correctly (or one that almost everyone answers incorrectly) will be rejected by the developer of a test of learning because it does not provide information with respect to an examinee's relative standing. Assessments for learning have the goal of revealing students' thinking within a much narrower content domain (the current target of instruction). Typically, more items from a given area of content are used because the goal is to be able to describe students' thinking rather than simply discriminating among different levels of mastery. We turn now to a discussion of a technology application with the potential to support assessments for learning.

Assessments for Classroom Instruction

In the remainder of this chapter, we explore technology's potential from the perspective of researchers interested in studying instructional processes and real-time instructional decision making. From this perspective, instruction is not a fixed regimen but a dynamic interaction among teachers and students that is emergent in its actual implementation. Rather than a canned presentation, instruction is viewed as an interactive activity, with the teacher making decisions in response to students' demonstration of interest or boredom, comprehension, or specific kinds of misconceptions (Cohen & Ball, 1999).

Researchers, instructors, and technology designers have begun to explore the requirements for quick, ongoing diagnosis of student skills or understanding within the context of instruction. Such tools are distinct from the student data analysis software described earlier in that they are intended to help teachers collect information about student understanding and skill within teacher-developed lessons *as part of the act of teaching*.

The question for the developer of software designed to support instructional practice is whether technology supports can supply teachers with better information concerning their students' thinking to inform instructional decision making "on the fly." We turn now to a more extended discussion of systems that attempt to support information flow within entire classrooms.⁴ These classroom instructional support systems make extensive use of feedback loops, a fundamental concept in computer, biological, and engineering sciences (Wiener, 1948) and one that is central to such common monitoring systems and self-regulation processes as the thermostat (Brandes & Wilensky, 1990; Roberts, 1978). As such, the basic structure of these systems differs from that of the many systems that embody a transmission or technology diffusion model.

CLASSROOM COMMUNICATION SYSTEMS

Skilled teachers have always elicited student responses and read facial expressions and body language to “take the pulse” of the class and of individual students. But the amount of information available to a teacher in a class of 30 students is limited.⁵ Both early classroom technologies (e.g., Suppes & Morningstar, 1968) and today’s commercial learning systems promise to make learning interactive by having each student respond individually to computer-generated questions or exercises presented by computer software that keeps track of the student’s every move and brings in new material at the optimal level of difficulty for that student. The technology uses described subsequently elicit a response from every student but do so in the context of a system that supports—rather than replaces—the teacher.

Systems designed to support better communication—and ultimately better teaching and learning—within classrooms have their origins in response systems developed more than 15 years ago. Such systems provide some form of input mechanism for each student in the class and include software that aggregates student responses and arranges them into a summary or display for the teacher and/or the entire class to view. With this kind of system, the basic idea is that every student responds to a question or task—not just the one individual who raises his or her hand or gets called on by the teacher—and it is possible to include many question-response-aggregation-display cycles within a given class period. Early classroom response systems found a receptive audience chiefly among instructors in large university science classes, where the contribution of this approach to student engagement and end-of-course performance levels has been documented (Abrahamson, 2000; Dufresne, Gerace, Leonard, Mestre, & Wenk, 1996; Truong, Griswold, Ratto, & Star, 2002). We describe the early systems as background for a description of newer systems—lower in cost, less intrusive, and no longer limited to multiple-choice questions—with greater potential for K–12 adoption.

Early Classroom Response Systems

Classroom response systems capable of supporting question-response-aggregation-display cycles have been marketed commercially for almost two decades. The early systems did not catch on with a large proportion of the K–12 market, however, because they were expensive and physically cumbersome and were associated with a form of instruction that most teachers regarded as limited—namely, the posing of a series of multiple-choice questions for student responses.

These limitations were illustrated vividly at a technology-oriented middle school we studied in the early 1990s (Means & Olson, 1995). The school’s founders had been eager to “break the mold” of conventional schooling and to demonstrate what could be done with new technology and a rethinking of school structures on the basis of what would best support student learning. A district administrator, impressed with the vendor’s description of the benefits of a classroom response system, purchased two for the space that was being remodeled to house the middle school. The result was two classrooms that looked very much like university lecture halls or corporate training rooms.

Semicircular rows of student seats canted upward from the instructor's stage. A counter in front of each row of seats held sets of response buttons for each student so that he or she could indicate a response for each question.

Unfortunately, the individuals who would be teaching the students had not been hired at the time the technology was purchased and so had not been consulted. They did not want to teach their middle school students through a series of multiple-choice questions. Some struggled valiantly to find a way to use the system that was compatible with their own instructional approach—using it for class brainstorming sessions rather than for multiple-choice questions, for example. In general, however, teachers did not find a satisfying way to use the system, and they were frustrated because the fixed classroom seats and counters did not permit flexible rearrangement for different kinds of student activities. No one wanted to teach in the classrooms outfitted with the expensive response system.

Advances in Communication Systems

In contrast to the response system just described, today's classroom communication systems⁶ have benefited from advances in technology, reduced price points, and the development of instructional approaches that better capitalize on a system's potential power. One of the first systems to add functionality to the basic classroom response system was a product called *Classtalk*. Classtalk permitted individual students (or groups) to work at their own pace through sets of questions and was able to handle open-ended question formats and structures for group collaboration.

Most of today's classroom communication systems use wireless connections between student units and the teacher. When using small, handheld student devices, classrooms are no longer restricted in the ways in which they can group students, as was the middle school just described. Students each have small, unobtrusive devices that can be used for real-time or near-real-time communication with the instructor and, sometimes, with other students. There is a mixture of a public display (such as a computer projection system) and a private display (i.e., on students' individual calculators, laptops, or handheld computers). The systems support the exchange of a range of data types, including not only text but also graphs, matrices, and images (Stroup et al., 2002). Moreover, they support rapid authoring of new activities by the teacher. In addition to these added functionalities, as computing power has dropped in price, so too has the price of these systems, bringing them within reach of many more K–12 schools. A classroom of 30 can now be equipped for as little as \$1,500, as compared with the six-digit price tag of the middle school classroom sets just mentioned. Major organizations entering this market include the Educational Testing Service, which purchased *Discourse*, a revised and expanded version of one of the earliest response systems, and Texas Instruments, which launched the *TI-Navigator* in 2003.

Use of Classroom Communication Systems in Higher Education

As noted, classroom communication systems found acceptance in higher education before making significant headway in the K–12 market. Universities were a more

receptive market for these systems because of their higher equipment budgets, the larger number of students in a single classroom (bringing down per student costs), and the example set by prominent faculty interested in trying out the systems as a possible alternative to the limited progress their students made in conceptually difficult content areas after a semester of conventional instruction.

The fact that these systems do nothing to replace the teacher (in terms of automating presentation of content or response to diagnostic information elicited from students) means that effective use of the systems, like that of most open-ended learning technologies, requires deep content knowledge on the part of the instructor. This feature too may make the systems less appealing to some K–12 teachers or to some administrators making technology purchase decisions. The systems are not conducive to top-down transmission of curriculum or policy.

The subject area that has seen the most active university use of classroom communication systems is physics. The conceptual difficulty of Newtonian physics is well documented (Confrey, 1990; Eylon & Linn, 1988; Halloun & Hestenes, 1985; McDermott, 1984). Students enter physics classes with a set of conceptions about the physical world that differ from the scientific account. Ordinary instruction fails to dislodge these conceptions, and many students leave traditional physics classes with fundamental ideas about motion that contradict the scientific theory they were assumed to have learned (Smith, diSessa, & Roschelle, 1993).

Eric Mazur, a Harvard physics professor, was one of the earliest to apply a classroom communication system to the problem of teaching physics for conceptual understanding (Crouch & Mazur, 2001; Fagen, Crouch, & Mazur, 2002; Mazur, 1997). Mazur taught introductory physics to premedical students and other nonmajors for more than a decade. When a reliable assessment of Newtonian concepts (the Force Concept Inventory, or FCI, developed by Hestenes) became available, Mazur administered it to his students, expecting that whereas students and professors at lower caliber schools might have problems, his students surely would not. Mazur was sorely disappointed when his students' FCI gains from the beginning to the end of his class were just as meager as those of students in every other traditional lecture setting in which the FCI assessment had been used.

With support from a classroom communication system, Mazur altered his lecturing style to devote about half of the class time to a technique he called "peer instruction." Rather than lecture continuously with little interruption from students, he would lecture for a short while and then pose a conceptual question (e.g., "Imagine holding two bricks below water. Brick A is just below the surface, while Brick B is at a greater depth. How does the force needed to hold Brick B in place differ from that needed for Brick A?"). After students had used the communication system to register their responses to the question, Mazur would invite them "to take a few minutes, turn to your neighbors, and convince them of your answer."

After the discussion, Mazur would have the class answer the same question a second time. Typically, the proportion of correct responses rose dramatically. (For example, in one class correct responses to the question in the example increased from 40%

to 80%.) Ideally, this is not the end of the process; the teacher now has the full attention of the class and can further explain and explore reasoning. For example, the teacher could ask "Are there any materials for which Archimedes's principle doesn't work? How can it be deduced from first principles?" However, unless they are actively engaged via the initial visible clash of opinions, students tend to ignore or misunderstand such explanations.

Mazur devotes most of his book (Mazur, 1997) to concrete advice on the strategic planning and classroom practice required for a teacher to implement peer instruction. He makes it clear that there is an art to designing good tasks and questions; in particular, the task must get to the heart of the conceptual matter and be neither too easy (or there is no need for discussion) nor too hard (which would result in an insufficient distribution of the correct answer among the class population). Mazur believes the technology's contribution resides in prompting students to think deeply enough about the question initially to commit to a response to the question and in making students feel comfortable in arguing for their response by making it clear that the class as a whole holds a range of opinions (as reflected in the projected histogram of student responses).

Mazur found that in the year he first implemented his peer instruction methods, the distribution of his students' scores on the FCI strongly shifted from pretest to posttest (Mazur, 1997). Impressively, after the posttest only 4% of the students were below the threshold of mastery as defined by the FCI. Moreover, Mazur reported a steady increase in his students' gain scores in each subsequent year he used this approach over a decade (Crouch & Mazur, 2001).

K-12 Uses of Classroom Communication Systems

A description of how a classroom communication system could support instruction at the elementary school level can be gleaned from Hartline's (1997) report on the practices of an elementary reading teacher in an inner-city school serving economically disadvantaged students. This teacher reported using a classroom communication system to check students' comprehension of reading passages. The teacher's routine for using the system started with asking students to read passages and then use the system to answer questions about the passages. When the students finished, she would open up discussion around conceptual issues by projecting a histogram of class responses to the first question. If students had different responses, she asked students to volunteer "clues" from the reading passage that could help explain or justify their particular answer choices. As students called out clues, she would write them on the blackboard next to the answer. Then students were invited to talk about which was the best set of clues and why one set of clues was more persuasive than another. After discussion, students could change their answers before the teacher projected a new histogram and introduced another cycle of discussion. In one semester of using the system, this teacher reported that in two fifth-grade classes, the number of students reading at or above grade level rose from 34% (as measured at the end of fourth grade) to 88% on the state-mandated test (Hartline, 1997).

Mazur's peer instruction and the reading class just described illustrate ways in which a classroom communication system supports use of multiple-choice questions as an impetus for exchange of views and rich classroom discussions. Today, a wider range of instructional strategies are possible because advances in technology have extended the kinds of student responses that can be registered and aggregated. Researchers are just beginning to explore the pedagogical strategies that this wider range of response options will support. Davis (2002), for example, reports using the Texas Instruments prototype network to exchange data sets that students gather with probes attached to their calculators. The examination and juxtaposition of different answers or understandings that Mazur and the reading teacher provoked with responses to multiple-choice questions can become even richer when alternative data sets are compared. Different students or groups of students may be taking the same kinds of measurements for different samples (for example, measuring the pH of different samples of rainwater, some taken from the same location and others from different locations). Differences in the various sets of readings can provoke questions about their different samples, variations in their technique, or statistical concepts such as variance and measurement error.

Roschelle and Pea (2002) describe systems in which students directly sketch on images, and their marks are aggregated into a composite image. This process can be used to gather instant feedback on spatial information. For example, a social studies teacher could display a map showing cotton- and rice-growing regions in the United States in 1850 and ask students to predict from that information which states would be the first to secede from the Union in the Civil War. The students' marks on their copy of the map on their handheld units could be transmitted to the teacher's map. On the teacher's map, the student marks appear as overlays, making the students' thinking visible in the aggregate and allowing the teacher to direct the conversation accordingly.

Davis (2002) reports that students can sketch graphs of functions or points on a curve, and the teacher can aggregate feedback on whether they understand the shape of the function. Stroup (1999) has extended the communication system to allow students to participate in a group simulation in which each student controls a different parameter or agent. This extension can allow students to explore the spread of disease and other distributed system phenomena. Kaput and Hegedus (2002) asked students to create functions that obey a particular constraint—for example, velocity graphs that show a 10-meter displacement in position. The resulting collection of submissions could be explored to reveal patterns in all possible answers—for example, that all such velocity graphs have the same area. Such innovative uses of classroom networks can be viewed as strategies for reorganizing classroom activity patterns in ways that focus student actions and promote cycles of reflection.

Using technology to inform classroom instruction does not require complex technologies. The technology needs primarily to provide teachers with a way to orchestrate an activity that gives students different ways to act and express what they know and can do. *Boomerang*, a tool developed by another group of teachers in South Carolina in combination with researchers from the Center for Technology in Learning, is a hand-

held software application that allows teachers to gather student questions about a topic and use them in instruction. Teachers use Boomerang to find out what knowledge students bring to a topic at the beginning of a unit and to have them write test questions to help them review material they have already learned. Students beam their questions to one another or to the teacher, and the teacher can display all of the students' questions using a document camera and overhead projector. The technology is easy for students and teachers to use, but it includes an important role for student questions in science class, something that researchers find is typically quite rare (Dillon, 1988). This is important in helping students learn the process of inquiry and in monitoring their comprehension of text and lectures (Davey & McBride, 1986; Dori & Herscovitz, 1999; King, 1991; Marbach-Ad & Sokolove, 2000).

It should be noted that research on these systems to date has featured mainly single-condition pre/post designs with instructor-developed tests or measures of student interest, sense of engagement, or satisfaction. The impact of these technology-supported instructional strategies on learning has yet to be evaluated in a rigorous fashion. Moreover, the more powerful, flexible classroom communication systems are just starting to be implemented in K–12 settings, and the many ways they could be used to support teaching and learning in a range of subject areas are just beginning to be explored. While it seems clear that such systems stimulate a greater sense of involvement in large lecture-based classes (Abrahamson, 2000; Dufresne et al., 1966), much remains to be learned about how teachers can and will use these systems and about their effects on learning in the smaller classrooms in which K–12 education takes place.

POTENTIAL POLICY CONNECTIONS

A case can be made that the uses of technology that have been most common in education to date are better characterized as extensions of education “business as usual” than as groundbreaking innovations. Teachers who embark on the integration of technology into their practice typically start by using these new tools to support the kind of teaching they have always done (Cuban, 2001; Sandholtz, Ringstaff, & Dwyer, 1997). Adding a technology course to the academic catalog or automating administrative processes may well be valuable, but neither is likely to transform schools. Moreover, the notion of technology as a policy tool—if the tool is conceived as a mechanism for disseminating policies and curricula determined at higher levels of the education system—is almost by definition an amplification of conventional activities and approaches.

Before concluding that technology's impact on education is weak, however, we should consider the record of technology introduction more broadly. Studies of technology adoption have shown that the near-term effects of newly developed technologies are typically overestimated, while long-term effects are poorly understood and grossly underestimated at the time the technology first comes into use (Brown & Duguid, 2002). We nearly always begin by using a new technology as a replacement for one that is more familiar (e.g., the “horseless carriage” or the refrigerator as “ice box”) and only over time come to appreciate the full range of potential uses and more

profound influences (e.g., the rise of shopping malls and suburbs in the case of the automobile). Our guess is that the same scenario will play out over time in regard to computer and network technologies in schools—we are witnessing an abundance of technology applications designed to increase standardization and efficiency within our current educational system and have only tantalizing glimpses of technology's potential transformative power.

We have argued that technology has the potential for transforming school learning opportunities (a) by providing more effective representations of core ideas in challenging content areas and (b) by informing classroom interaction patterns in ways that better connect student thinking and teacher instructional decisions. Although technology may be a necessary support in terms of providing teachers with knowledge of students' thinking, it is far from sufficient in terms of providing the interactive instruction described earlier. The way in which the instructor shapes classroom activities and the quality of the exercises or questions to which students respond are critical. It remains to be seen whether and how new technologies can support teachers in their moment-to-moment instructional decision making, but we view this as an exciting new area for research.

We have stressed technology's potential for amplifying the amount of information teachers have about their students' understanding of the topic at hand. The descriptions provided here suggest ways in which teachers can collect this information systematically from every student as a natural part of instruction. In addition to their role in informing instruction, the products of student thinking collected by the new technologies as instruction is unfolding could be gathered and used as evidence of student strengths and weaknesses. Herein lies the potential for connecting the various levels of the education system (Pellegrino et al., 2001). Classroom formative assessments of student thinking should be designed first and foremost with the goal of supporting instructional decision making. We have noted that fulfilling this goal requires more information about student understandings (and misunderstandings) in a narrow content area than is needed in assessments of learning for accountability purposes. In a well-aligned system, however, the detailed diagnostic information obtained to inform instruction pertains to an area of knowledge or competency that is contained within the standards promulgated at higher levels of the system (i.e., by the district or state or by national standards-setting bodies). Across time, the evidence of student understanding collected as part of classroom instruction in a large set of content areas would in fact constitute ample evidence of student learning in a domain. Because technology can capture, organize, and store samples of student thinking and behavior, there is, in principle at least, the potential for supplementing or even replacing much of the "drop-in-from-the-sky" assessment that is the mechanism for today's accountability systems (Bennett, 1998).

Today, we see technology being used to link classroom practice and state accountability systems by delivering proxies for state standardized tests in the classroom as often as twice a week. Tomorrow, we can imagine a system in which technology-supported instructional activities can be organized and abstracted to give policymakers the infor-

mation they want concerning what students know and can do in combination with data on the nature of students' understanding and the kinds of instruction they have received. Systematic documentation of individual students' understanding and competency in an area over time could in fact help support a better understanding of cognitive development within specific academic domains. Under these circumstances, educational standards could be developed to reflect not only priorities set at higher levels of the education system but also knowledge of trajectories of student learning developed from the bottom up. In the long run, technology's contribution to education policy may be through provision of infrastructures that explicitly support systems of mutual influence, with information moving not just from top to bottom (from federal to state, district, school, and classroom levels) but also from bottom to top. Such an alternative approach to documenting student accomplishments, coupled with greater diagnostic information to support teachers' decision making during instruction, could potentially have a profound impact on the nature of schooling.

NOTES

¹ A number of specific technology products are mentioned by way of illustrating the various uses of technology described in this chapter. No endorsement of these products or claims for their efficacy should be inferred from the fact that they are mentioned.

² We developed these categories to highlight alternative ways of thinking about what technology can do for education. We recognize that category boundaries may be fuzzy, and individual applications or interventions may address multiple goals.

³ An important example where technology has reached widespread scale as a curriculum resource and has achieved strong perceived value across many stakeholders is the graphing calculator. These \$100–\$200 devices enable students to graph equations, plot data, construct geometric sketches, and solve mathematical problems. Approximately 40% of all U.S. high school students now have graphing calculators, and these tools have been fully institutionalized through incorporation into textbooks, teacher professional development offerings, and policy documents such as the principles and standards of the National Council of Teachers of Mathematics (according to which “technology is essential”). A clear sign of the graphing calculator becoming an essential curriculum resource is that students are now required to have one to take advanced placement courses and tests. Another noteworthy characteristic of the graphing calculator as a policy instrument is that its low price has enabled a focus on helping students achieve more in mathematics without creating a digital divide.

⁴ Zuboff (1989) draws a distinction between uses of technology that automate existing practices and those that provide new information that supports new practices. Zuboff refers to the latter as “informing” technologies.

⁵ While a teacher does not necessarily need to know the precise level of understanding of every single student to decide that a topic needs to be readdressed through a different strategy, there is ample evidence that teachers who rely on the remarks and body language of just a few students are often overly sanguine about the class's level of comprehension (Mazur, 1997).

⁶ The term “classroom communication systems” has evolved as the most common description of these more flexible descendents of the earlier response systems.

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