HANDBOOK OF
EDUCATIONAL PSYCHOLOGY

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A Project of Division 15,
The Division of Educational
Psychology of the American
Psychological Association

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LOOKING AT TECHNOLOGY IN CONTEXT:
A FRAMEWORK FOR UNDERSTANDING
TECHNOLOGY AND EDUCATION RESEARCH

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This chapter discusses technology and its role in education. Questions that we raise and attempt to answer are: What do we know about the effects of technology on student learning and educational practice? What will future research on technology look like, and how might it differ from what has been done in the past?

It is extraordinarily challenging to attempt answering these questions. From our perspective, informed answers require a simultaneous exploration of at least three areas: (a) technology, (b) theories of human potential and human learning, and (c) issues of educational practice. These areas, and their intersections, are illustrated schematically in Figure 25–1. The challenge of discussing the areas in Figure 25–1 is increased by the fact that each has undergone major change during the past 10 to 15 years. In particular:

- **Technology.** Computer, video, and telecommunication systems available today were hard to imagine even 10 years ago. Many argue that the rate of change is increasing, making it almost impossible to foresee what will be possible within even a short span of time (e.g., Nickerson & Zodhiates, 1988; Nair, 1994). At the same time, Becker (1994) indicates that much of the latest technology has not reached the schools.

- **Learning Theory.** Visions of technology look very different, depending on the tacit or explicit theories of learning that guide their design and implementation (e.g., Collins, 1996; Duffy, Lowyck, & Jonassen, 1993; Hofmeister, Camine, & Clark, 1993; Hooper & Hannafin, 1991; Means et al., 1993; Newman, 1990a, 1990b; Nix & Spiro, 1990; R. D. Pea, 1992; Regian & Shute, 1992; Salomon, 1992; Salomon, Perkins, & Globerson, 1991; Spiro & Jelmg, 1990; Spiro, Feltovich, Jacobson, & Coulson, 1991; Spiro, Vispoel, Schmitz, Samarakun, & Boeger, 1987). Theories of learners and learning have undergone radical change during the past one and a half decades, and this has important implications for how technology-based applications are used and assessed.

- **Educational Practice.** The primary goals of education have changed in the past one and a half decades, and the implications of these changes must be understood by researchers. Perhaps the most important shift involves the assumption that all students, not just a select few, must be prepared to be lifelong learners and hence must learn to think, learn, and reason on their own (Resnick, 1987a). This requires a shift from an exclusive focus on basic skills to one that emphasizes the use of relevant skills and knowledge in the context of pursuing meaningful learning and problem-solving goals.

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*The Cognition and Technology Group at Vanderbilt (CTGV) refers to an interdisciplinary group of individuals at the Learning Technology Center, Peabody College at Vanderbilt University. The framework discussed in this chapter was developed by the Co-Directors of the Center: John Bransford, Susan Goldman and Ted Hasselbring. Members of the CTGV contributing to this chapter are the following (in alphabetical order): Brigid Barron, Linda Barron, Olin Campbell, Nathalie Coté, Thad Crews, Laura Goin, Elizabeth Goldman, Rachelle Hackett, Daniel Hickey, Cindy Hmelio, Ronald Kantor, Xiaodong Lin, Cynthia Mayfield-Stewart, Allison Moore, Joyce Moore, Mitchell Nathan, James W. Pellegrino, Faapio Poe, Anthony Petrosino, Daniel Schwartz, Teresa Secules, Diana Sharp, Robert Sherwood, Carolyn Stalcup, Laura Till, Sashank Varma, Rosa Volpe, Nancy Yve, Susan Williams, and Linda Zech. The comments of Ellen Mandinach and Gabriela Salomon on earlier drafts of this chapter were extremely helpful.
(e.g., Resnick & Klopf, 1989). This shift affects curriculum, instruction, and assessment in all subject areas taught in school (J. D. Bransford, Goldman, & Vye, 1991). As we shall see, this shift also requires efforts to connect students and teachers to the broader community (Ramirez & Bell, 1994b).

The challenge of discussing technology, learning theory, and education is increased by the fact that all three areas interact with one another. Changes in theories of learning affect uses of technology, but new technologies also make new kinds of interactions possible and hence affect theories of learning (e.g., Kozma, 1994; Salomon, 1993b, 1993c). These changes affect issues of assessment as well (e.g., A. L. Brown, Campione, Webber, & McGilly, 1991; Collins, Hawkins, & Frederiksen, 1993–1994; S. R. Goldman, Pellegrino, & Bransford, 1994; Hawkins, Collins, & Frederiksen, 1990, Salomon, 1991). Similarly, changes in technologies affect educational policy, and vice versa. For example, several years ago it appeared that all students needed to learn some type of computer language such as BASIC or COBOL to be prepared for the work force. Today, applications are much more user friendly, and workplace success is less dependent on traditional programming skills.

We agree with Sheingold’s (1991) argument that the areas of technology, educational policy, and learning theory need to be considered simultaneously:

The agendas of active learning, technology, and (a push for) restructuring—each a powerful vehicle for changing learning and teaching in schools—need to be pursued concurrently to be maximally effective. If we imagine all three coming together in schools and districts, the potential for synergy is very great indeed. (Sheingold, 1991, p. 27)

The need to consider three areas simultaneously creates interesting challenges for research in education. For example, traditional research in educational psychology has focused on the individual, and often only the cognitive characteristics of the individual. Treatment variables are defined with respect to particular educational practices, and experimental studies examine their effects on individual performance. Under this model of educational research, technology is just another treatment variable. Changes in technologies, theories of human learning, and the goals of education make it quite difficult to maintain the traditional view of educational psychology research. The simultaneous consideration of practice, theory, and technology implies new learning environments that are much more complicated to study than are traditional research designs (Mandinach & Cline, 1994; Salomon, 1992). This added complexity calls for new ways of thinking about research on technology and education.

FOCUS OF THE PRESENT CHAPTER

A major goal of this chapter is to present a framework for approaching research that accommodates traditional as well as expanded investigations of learning, technology, and educational practice. However, the need to consider three different subject areas, each of which has undergone major changes, means that we have been forced to make certain choices about what is included in this chapter. Before presenting our framework, we outline what we do not attempt to do.

1. We do not attempt an exhaustive review of all literature relevant to technology, education, and theories of learning. If we published nothing more than a bibliography of relevant studies, we would exceed the page limitations for this chapter.

2. We do not attempt to provide detailed information about any particular technology-based application. For example, we do not provide complete descriptions of Anderson and colleagues’ geometry tutor (Anderson, Boyle, & Yost, 1985; Koedinger & Anderson, 1993), Papert’s LOGO (1980), Bank Street College of Education’s Voyage of the Mimi (1984), Salomon’s Writing Partner (1993c), Scairdamalia and Bereiter’s CILE (Scairdamalia, Bereiter, McLean, Swallow, & Woodrufl, 1989), Biiice and Rubin’s QIILL (1993), and so forth. Instead, we provide relevant references that allow readers to read about these programs in more detail.

3. We do not attempt to provide methodological critiques of studies using technology. We discuss general methodological issues (e.g., R. Clark, 1983; R. Clark & Salomon, 1986; R. Clark, 1994), but we do not evaluate the methodology of specific studies per se. The field seems to be in transition stage, moving from small, well-defined studies of individual students to classroom-based and school-based “design experiments” (e.g., A. L. Brown, 1992; A. L. Brown et al., 1993; Hawkins & Collins, in press; Mandinach & Cline, 1994). These ventures raise methodological issues that are just beginning to be recognized and understood (Lamon et al., in press; Salomon, 1992).

In this chapter we explore the interplay among technology, educational practice, and theories of learning. Decisions about each of these areas are involved in any attempt to design, implement, and evaluate uses of technology for education. But these decisions are often tacit. As Collins (1996) argues, it is better to make one’s decisions explicit so that they can be consciously considered and, when appropriate, subjected to empirical testing.

In the discussion that follows, we limit our scope to electronic technologies that have become available since the 1960s; hence, we do not consider technologies such as the printing press and traditional audiovisual devices such as the overhead projector, slide projector, radio, and closed-circuit television. The framework of our discussion is designed to focus attention on the fact that research questions and methodologies change...
as a function of changes in technology, theories of learning, and issues of educational practice. It is a framework for looking at technology in the context of learning theories and research settings and is called the LTC framework, for looking at technology in context.

### A FRAMEWORK FOR LOOKING AT TECHNOLOGY IN CONTEXT

Our discussion of past and future trends in research will be organized around the framework illustrated in Figure 25–2. The LTC framework—looking at technology in context—focuses on the intersection of technology, learning theory, and educational practice. It does so by considering the matrix created by two dimensions of context. The columns in the LTC framework represent issues of educational practice; they have to do with the educational contexts within which research is situated. The rows represent the theoretical context; they highlight issues relevant to learning theory, including theories of human potential, and pedagogy. The LTC framework is discussed in more detail below.

#### Educational Contexts in Which Research Is Situated

The columns of the LTC framework represent the *educational contexts* in which various programs are situated and studied—contexts that range from isolated laboratory settings to classrooms to connected sets of schools. The LTC framework includes three categories along the contexts of usage dimension: (a) *in vitro* laboratory settings, (b) *in vivo* settings, involving individual classrooms or sometimes schools, and (c) *connected* settings, involving sets of connected classrooms and schools. When one works in these different settings, different theoretical and practical issues become relevant, as described below.

- **In vitro laboratory settings** include experiments conducted in university-based research laboratories as well as experiments in schools where researchers do the teaching and assessment in order to test particular ideas. The advantages of this context include greater experimental precision and fidelity of implementation; however, many issues that are important for educational success might never be addressed (see below).

- **In vivo classroom settings** include studies conducted in individual classrooms by classroom teachers. A research team may collect the data, but the intervention is managed by the teachers rather than the researchers from the laboratory. This type of arrangement raises a host of important new issues. For example, researchers who have moved from the laboratory to classroom settings have discovered that their programs may require more extensive professional development for administrators and classroom teachers than was anticipated, or may require a restructuring of typical school schedules from 50-minute class periods to larger blocks of time (e.g., see chapters in Hawkins & Collins, in press; Lamon et al., in press; McGilly, 1994).

- **Connected settings** consist of connected classrooms and schools; studies conducted in them explicitly attempt to re-

<table>
<thead>
<tr>
<th>In Vitro Laboratory</th>
<th>In Vivo Individual Classes and Schools</th>
<th>Connected Classes, Schools, Communities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Models</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Constructivist Models: Part of School Day</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Constructivist Models: All of Schooling</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

Cell 1: Studies of drill and practice programs in math, spelling, or particular content areas that are administered by research staff.

Cell 2: Studies of drill and practice programs in math, spelling, or particular content areas that are administered by classroom teachers.

Cell 3: Studies of distance learning connecting various classrooms that involve lectures and traditional tests.

Cell 4: Studies of constructivist-oriented programs (e.g., Logo, Voyage of the Mimi, Jasper) where the teaching and assessment are conducted by research staff.

Cell 5: Studies of constructivist-oriented programs (e.g., Logo, Voyage of the Mimi, Jasper) where the teaching and assessment are conducted by regular classroom teachers.

Cell 6: Studies of constructivist-oriented programs (e.g., Logo, Voyage of the Mimi, Jasper) where the teaching and assessment are conducted by regular classroom teachers and the classrooms are linked through telecommunications and interact on the project involved.

Cell 7: Studies of constructivist-oriented programs that fill the entire school day and take place in an experimental school with specially trained staff.

Cell 8: Studies of constructivist-oriented programs that fill the entire school day and take place in normal classrooms; however, the classrooms tend to operate independently of one another.

Cell 9: Studies of constructivist-oriented programs that fill the entire school day and take place in linked classrooms that interact on common problems and projects.


believe the isolation of classrooms and schools and connect them to form broad-based learning communities. An important reason for creating learning communities is to attempt to deal with issues of equity (e.g., Hawkins, 1991; Hawkins & Sheingold, 1985). Many schools do not have access to teachers of specialized subject matters or to a broad range of reference materials. If classrooms are connected, scarce resources can be shared. A second reason for connecting classrooms is that they provide authentic audiences that allow students to share...
ideas, data, and opinions (e.g., Bruce, Peyton, & Batson, 1993; Cognition and Technology Group at Vanderbilt [CTGV], 1994a; J. A. Levin, Kim, & M. M. Riel, 1990). A third reason for connecting classrooms is to facilitate the professional development needed to begin and sustain educational reform. This includes issues of "scaling up" and moving beyond "laboratory" or "hothouse" schools (e.g., CTGV, in press; Hawkins & Collins, in press; Mandinach & Cline, 1994).

As noted earlier, each type of educational research context within the LTC framework has unique advantages and disadvantages. The primary advantage of working in laboratory contexts (cells 1, 4, and 7) is that one can control important sets of variables and ensure high degrees of fidelity of program implementation. The disadvantage of working in these cells is that many issues relevant to real classrooms and real schools are not dealt with, thereby limiting the applicability of the findings to real classroom settings.

Researchers who have moved from laboratories to real classrooms have discovered that their programs may:

- motivate students only when they are special events, not when they are a part of regular classroom practices;
- work well when there is a small researcher-to-student ratio, but not in classrooms with one teacher and 20 or more students;
- require levels of professional development for administrators and classroom teachers that were unanticipated;
- require a restructuring of typical school schedules (e.g., typical 50-minute class periods may not work);
- produce gains that are not measured by the typical achievement tests used for accountability; and
- require research methodologies (e.g., ethnographic analysis) that are new to researchers schooled in traditional laboratory research.

Migrations from laboratory to classroom settings have also raised new issues of research methodology. In laboratory settings, each individual often receives an experimental treatment that is independent of the treatment given to any other individual. In contrast, in classroom-based research, groups of children within a classroom usually receive the same treatment. Therefore, students are not independent of one another, and research conducted in actual classrooms requires one to think of the classroom as a unit. When one works with connected sets of classrooms (cells 3, 6, and 9), one can no longer assume the independence of classrooms. Although there are methods for handling these dependencies, such as hierarchical linear modeling (e.g., Bryk & Raudenbush, 1992), researchers need to be more cognizant of them and, more generally, of the need to employ multiple methodologies and convergent measures (e.g., A. L. Brown, 1992; Lamon et al., in press; Mandinach & Cline, 1994; Salomon, 1991). Discussions of the theoretical, practical, and methodological issues involved in research in real classrooms can be found in a number of articles, including CTGV (1992d, in press), Blumenfeld et al. (1991), A. L. Brown (1992), Hawkins & Collins (in press), Lamon et al. (in press), Schofield, Evans-Rhodes, & Huber (1990), and Salomon (1991, 1992).

Theoretical Context of Applications

The rows of the LTC framework represent the theoretical context of technology-based applications. The theoretical context affects assumptions about curriculum, instruction, and assessment. These assumptions have important implications for implementation and research efforts.

Especially important is the congruence between the theoretical context of a particular program and the educational context or setting (laboratory, classroom, connected classrooms) in which the program is placed. When the theoretical context and the setting are congruent, it is easy to incorporate one's application into the context of existing practice. When the assumptions of the program and the setting are incongruent, the challenges are greater because of the need to transform traditional classroom practices.

For purposes of the present discussion, we assume that most classroom practices are consistent with transmission models of instruction rather than constructivist-oriented models (these models are discussed in more detail in the second and third sections of this chapter). As Greeno (1991) states: "In most schools, what students mostly do is listen, watch, and mimic things that the teacher and textbook tell them and show them" (p. 81). When technology programs are congruent with transmission models, they can be assimilated quite easily into traditional classroom settings. The first row of the LTC framework reflects implementations of technology that can be assimilated without fundamental change in theoretical perspectives on learning, instruction, and assessment.

Technology implementations that are based on constructivist theories cannot simply be assimilated into traditional classroom practices. Instead, the classrooms must be transformed (e.g., Bereiter, 1994; Bransford et al., 1991; Cobb, 1994; Cobb, Yackel, & Wood, 1992; Collins, 1991b; Pea, 1992; L. B. Resnick & Klopf, 1989; Savery & Duffy, in press). The LTC framework emphasizes that there are multiple levels at which transformation can be attempted. The challenges increase as one moves from attempts to transform only part of the school day (row 2) to attempts to transform the entire nature of schooling (row 3). These efforts include attempts to transform linkages between schools and the home and community, as well as transform what happens in classrooms.

Combining the Two Dimensions of Context

Combining the two dimensions of context—the educational and the theoretical—yields nine cells in the LTC framework. These cells can be used to characterize a vast array of possible studies. Examples of the kinds of studies that fit in each cell are provided in Figure 25-2. By situating a study in a particular cell (one cannot do this with 100 percent certainty but one can do it approximately), what emerges is a better picture of what has been learned and how that information can be generalized. In the following discussion we use the LTC framework to organize discussions of the theoretical issues, research findings, and research prospects related to technology. We begin with the
first row of the LTC framework, which represents some of the historically earlier work on technology.

THEORY AND RESEARCH RELEVANT TO TRANSMISSION MODELS OF LEARNING

Our goal in this section is to summarize some of the research relevant to the transmission models of learning (cells 1, 2, and 3, in the LTC framework). This research began in the early 1960s using mainframe computers, with subsequent “downsizing” to mini- and microcomputers as they became available. Most of this research was guided by a transmission theory of the nature of teaching, learning, and assessment. We discuss this theory in more detail below.

Theoretical Context of Row 1: Transmission Models of Learning

The early pioneers who conducted research on technology and education took existing classroom practice as a given and attempted to use technology to make it more efficient. Most classroom practice was consistent with what has come to be called a transmission model of instruction and assessment. Sometimes the work was conducted in laboratory settings (cell 1), and sometimes it was conducted in classroom settings that were either independent of one another (cell 2) or connected (cell 3). Work relevant to cell 3 involved experiments in distance learning whereby multiple classrooms were linked to a single instructor and the instructional design and pedagogy involved “transmission at a distance.”

Transmission models are based on assumptions that:

- learning involves the accumulation of particular sets of facts and skills;
- teaching involves the transmission of facts and skills by an expert; and
- assessment involves an accounting of whether the desired facts and skills have been acquired.

These assumptions are consistent with the dominant psychological theory of learning in the United States from the early 1900s until the late 1960s, which was actually a class of theories known as behaviorism, as exemplified in the work of B. F. Skinner (1953; Keller & Schoenfeld, 1950) and James Holland in education (e.g., Holland & Skinner, 1961). The root metaphor of behaviorism was an organism whose behavior was a product of the contingencies that existed in the environment. Learning was the result of a lifetime of accumulating associations between behaviors and their consequences. Rewards for desired behaviors increased their frequency; appropriate responding could be shaped through the reinforcement of behaviors that successively approximated the desired behaviors. For reward mechanisms to operate in the intended manner, discrete sets of target behaviors had to be specified.

Transmission models are also consistent with the metaphor of education as an industrial assembly line, according to which students progressed along a moving assembly line as they proceed from kindergarten through Grade 12 and, for some, college. At particular points in the assembly line, specific sets of skills and knowledge were introduced to the students. Over time, students would accumulate as much knowledge and skill as their capacities allowed.

Classroom environments based on transmission models usually involve students who adopt the role of receivers of wisdom that is dispensed by teachers, textbooks, and other media (A. L. Brown, 1992; Means, 1994). The role of the teacher is to deliver information and manage learning. The role of the student is to engage in “knowledge telling” (Bereiter & Scardamalia, 1989; Scardamalia & Bereiter, 1991) and demonstrate that what has been transmitted has been retained. Usually, everyone is taught the same thing at the same time, although there is some room for individualization with respect to the speed of learning specific sets of skills and competencies. Assessments typically measure how much each student has learned by assessing discrete sets of facts and skills.

Three Areas of Research Relevant to Transmission Models

Over the past three decades, research on three types of technology implementations has dominated investigations that fit within the first row (transmission models) of the LTC framework. We first provide an overview of these areas; later we discuss the findings from and issues associated with the research.

Computer as Delivery Mechanism: Computer-Assisted Instruction. The first type of implementation took traditional curricula and delivered them by computer (initially mainframe computers; subsequently mini- and microcomputers). The purpose of the research on these implementations was to determine if instruction delivered by computer would be as good as or better than instruction delivered by a teacher, either in place of or in addition to traditional instruction. In other words, could technology make knowledge transmission occur more efficiently than it did when delivered by a human? Much of this research occurred in classroom settings (cell 2 of the framework), but some, mostly pilot studies conducted by software developers, occurred in laboratory settings (cell 1). Pedagogy was largely drill and practice of traditional skills, with some emphasis on well-defined tutorials in the style of programmed instruction (e.g., Holland & Skinner, 1961). The bulk of the large-scale evaluation studies conducted on computer-assisted instruction (CAI) focused on technology implementations of this type. Effects were measured by increased accuracy, distinguishing this kind of research from work on component skills, discussed below.

In the late 1970s and early 1980s, new variants of CAI were stimulated by cognitive theories of complex cognitive skill acquisition (Anderson, 1982, 1987; Anderson, Conrad, & Corbett, 1989; Schneider & Shiffrin, 1985). These theories analyzed complex skills into their components and stressed the importance of fluency (not just accuracy) in executing these components (e.g., S. R. Goldman, Pellegrino, & Mertz, 1988; LaBerge & Samuels, 1974). For example, Hasselbring, Goin, and Bransford (1988) showed that, with respect to accuracy in basic math facts, special needs students began to catch up with regular education students between the first and eighth grades. How-
ever, with respect to speed of responding (fluency), differences between special needs and regular education students increased over the grades.

Computer Programming and Literacy. The second type of technology implementation treated computers as a subject matter area and was conducted in classroom contexts. These implementations were stimulated by the increased availability in the early 1980s of microcomputers (e.g., Commodore 64, Tandy, Apple II and Ile). Computer literacy and computer programming courses appeared more and more frequently (e.g., Luehrmann & Peckham, 1983). Research focused largely on the effects of learning to program computers on students’ thinking. It is noteworthy that national surveys of computer usage continue to show that the dominant uses of computers in schools are for programming and drill and practice, reflecting little change over the past 15 years (Becker, 1983; 1984a, 1984b; 1984c; 1991, 1994; Cosden, Gerber, Goldman, D. S. Semmel, & M. I. Semmel, 1986; Cosden, Gerber, D. S. Semmel, Goldman, & M. I. Semmel, 1987).

Distance Learning. The third type of technology implementation is distance learning that delivers traditional, transmission model instruction to multiple sites (cell 3 of the LTC framework). Such education emphasizes student autonomy, independence, and isolation (e.g., Barker, 1991; Barker, Frishie, & Patrick, 1989; Garrison, 1989; 1993; L. M. Harasim, 1990; Hawkins, 1991; Hiltz, 1986; Holmberg, 1988; Moore, 1989). Research examines the effect of distance learning on student achievement. For the most part, the findings confirm that there is no significant difference in student achievement between one technological delivery system and another when the theoretical basis for instruction is a transmission model (e.g., Barker & Bannon, 1992; Hezel & Associates, 1993; Hiltz, 1986; Hobbs & Osborn, 1988; Hobbs, 1990; Holznagel, 1990; Moore, 1989; Sisung, 1992; Tushnet, Uriarte, Manuel, & Broekhuizen, 1993).

Evaluation Research on Computer-Assisted Instruction

We consider the evaluation of CAI from a historical perspective. In the late 1960s and early 1970s, several large-scale evaluations of CAI were conducted in which elementary schoolchildren were given 10 to 20 minutes of CAI instruction daily. In almost all cases, researchers reported that, compared to traditional instruction, CAI produced equivalent or superior results on standardized measures of achievement when effects were corrected for time spent in instruction (Atkinson, 1968; Suppes & Morningstar, 1968).

In the late 1970s, the Educational Testing Service (D. Alderman & Mahler, 1973; D. L. Alderman, 1978; Murphy & Rhea-Appel, 1977; Swinton, Amarel, & Morgan, 1978) evaluated the implementation of two major computer-based instructional systems in community colleges, PLATO (Programmed Logic for Automatic Teacher Operations; Alpert & Bitzer, 1970; Eastwood & Ballard, 1975) and TICCIT (Time-shared, Interactive, Computer-Controlled, Information Television; Bunderson, 1975). The two projects differed in several ways. PLATO was a large educational network supporting nearly 1,000 terminals, each accessing content from a central library. Classroom teachers, coordinated by PLATO central staff, were involved in the preparation of the lessons. TICCIT, on the other hand, was a small, local facility that used minicomputers and television receivers. Teams of specialists, including teachers, produced the courseware. Both systems successfully produced advanced instructional programs capable of serving many students at one time and may be seen as precursors to today’s integrated learning systems (ILSs).

Although these early evaluation studies produced some valuable information on the effects of CAI, the results of many studies were inconsistent and the conclusions drawn by the investigators were often unclear. In an attempt to gain a better understanding of the effect of CAI on achievement, reviews were written to bring the separately published studies together to reveal the common findings. These early reviews used a box score technique for integrating the results. These box score reviews generally reported the proportion of studies that were favorable and unfavorable toward CAI, as well as narrative comments on the studies.

Box Score Reviews. In one of the first box score reviews, Vinsonhaler and Bass (1972) summarized the results of 10 major studies conducted from 1967 to 1970 involving CAI drill and practice with more than 10,000 elementary schoolchildren from different sections of the country. The investigators concluded that children who received computerized drill and practice generally showed performance gains of 1 to 8 months over control children who received only traditional instruction.

The Vinsonhaler and Bass conclusions were supported in a later review by Edwards, Norton, Taylor, Weiss, and Dusseldorp (1975), who evaluated the effects of drill-and-practice, problem-solving, simulation, and tutorial computer instruction programs for producing achievement gains in schoolchildren. Based on results from six studies, they concluded that CAI plus traditional instruction was more effective than traditional instruction alone. CAI as a substitute for traditional instruction produced positive effects in nine studies and no difference compared with traditional instruction in eight others. Two studies in this review indicated that CAI drill-and-practice programs were more effective for low-ability students than for children of average ability. These reviewers noted that CAI reduced the time it took students to learn. They concluded that CAI produced better results than did traditional instruction on end-of-course examinations but not on retention examinations.

Similarly, Jamison, Suppes, and Wells (1974) concluded that when CAI was used as a supplement to traditional instruction at the elementary level, achievement scores were improved, especially for disadvantaged students. At the secondary and college level, the investigators concluded that CAI was at least as effective as traditional instruction, and in some cases CAI resulted in substantial savings in student time.

Although the box score reviews provided additional insight into the fundamental questions regarding the effectiveness of CAI, this type of review was shown to have limitations. For example, the box score reviews did not say how much better one method was than another; they simply reported how often a particular method came out on top. Further, they did not use statistics to find the characteristics that distinguished studies with positive results from those with negative findings. In an
A FRAMEWORK FOR UNDERSTANDING TECHNOLOGY AND EDUCATION RESEARCH • 813

attempt to overcome the limitations of box score reviews, researchers employed a more sophisticated meta-analysis approach where differences between treatments were reported in effect sizes.

**Meta-analyses.** Several meta-analyses were conducted in the late 1970s and early 1980s that examined the effects of CAI on student achievement (Burns & Bozeman, 1981; Hartley, 1977; J. Kulik, C. Kulik, & Cohen, 1980; J. A. Kulik, Bangert, & Williams, 1983). In each of these meta-analyses, the reviewers reported moderate positive effects for the CAI treatment. Burns and Bozeman (1981) used meta-analysis to integrate findings on CAI in mathematics teaching in elementary and secondary schools. They found that computer-based tutorials raised achievement test results by 0.45 standard deviation (SD) and that computer-based drill and practice raised test scores by 0.34 SD. In a summary of their analysis, Burns & Bozeman (1981) wrote:

> While no ultimate answers related to CAI effectiveness can be presented, the analysis and synthesis of many studies do point to a significant enhancement of learning in instructional environments supplemented by CAI, at least in one curricular area—mathematics. (p. 37)

J. A. Kulik et al. (1983) reported that when CAI was used in instruction, student scores on final examinations were raised from the 50th to the 63rd percentile, representing a 0.32 SD increase. In addition, Kulik and colleagues reported that student attitudes toward the subject being learned and student ratings of the quality of instruction were slightly more favorable with CAI. As well, students’ attitudes toward computers were significantly more positive as a result of CAI.

**Attempts to Understand the Benefits of Technology.** As research on technology progressed, researchers began to ask why CAI advantages occurred. One possible explanation for the reported positive effects of CAI on student achievement was presented by Bright (1983). He made a strong argument for explaining the “CAI phenomenon” and its positive effect on student achievement using data from the Beginning Teacher Evaluation Study (Denham & Lieberman, 1980). Bright (1983) argued that when academic learning time (ALT) is increased there is a concomitant gain in student achievement. Academic learning time is defined as the amount of time the student is engaged in a task and is highly successful in completing the task. Bright argued that ALT appeared to be a mediating variable for achievement. That is, the more ALT a student accumulated, the more the student learned.

Bright suggested that the many CAI activities could lead to an increase in ALT. For example, the amount of ALT was often increased by providing the student with an exciting computer-based learning environment through games or adventures while at the same time providing learning tasks in which the student could be highly successful. Bright argued that the combination of high-engagement time and high success rates correlated with student achievement. Hence, the very nature of many CAI activities could lead to an increase in ALT and achievement.

A second but related class of explanations of the positive effects of CAI has to do with the motivational context established by some of the programs. Many drill-and-practice programs include gamelike features that presumably motivate continued use of the software (Lepper & Chabay, 1985; Lepper & Malone, 1987). Although these gamelike features may promote continued use of the software, they are external rewards and do little to help, and may even work against, the development of intrinsic motivation. For some students the motivational “bells and whistles” may create a confusing environment that interferes with task performance (e.g., Christensen & Gerber, 1990).

Researchers who emphasized speed as well as accuracy provided another explanation for the benefits of technology. They examined whether speed of responding increased in the context of drill and practice on such component skills as arithmetic facts (S. R. Goldman et al., 1988; Hasselbring et al., 1988), word recognition (Frederiksen, Warren, & Rosebery, 1985; Roth & Beck, 1987), and spelling (English, Gerber, & Semmel, 1985; Hasselbring, 1984). The bulk of these studies found that speed of responding did increase over time, with no loss of accuracy. Weaker but significant positive effects were shown for the positive impact of increased fluency in the components on the complex cognitive skills of which they were a part. However, these effects were much less consistent across studies than the direct effects of drill and practice on the components, largely owing to the importance of planning and monitoring in the execution of the complex cognitive skill (cf. S. R. Goldman & Pellegrino, 1987; Hasselbring et al., 1987–1988, 1991).

Research also suggests that some design principles for creating skill-based software are especially important for special needs students. For example, beginning with a small set of to-be-learned items, rather than picking randomly from a larger set (e.g., Bjork, 1979; Torgeson, 1984; Torgesen & Young, 1983), has been shown to be very beneficial for students who have trouble mastering basic skills (Hasselbring et al., 1988).

**Methodological Confounds.** At the same time that Bright was suggesting that a CAI phenomenon existed, Clark (1983; Clark & Salomon, 1986) was arguing that studies comparing CAI with traditional classroom instruction were basically meaningless because they were hopelessly confounded. Clark argued that the experimental and comparison groups differed not only with respect to the availability of media (e.g., computers), but also with respect to the exact nature of the instruction provided. Based on a review of the literature, Clark suggested that there was no evidence to support the conclusion that media influenced learning and achievement under any conditions. Clark (1983) stated,

> The best current evidence is that media are mere vehicles that deliver instruction but do not influence student achievement any more than the truck that delivers our groceries causes changes in our nutrition. Basically, the choice of vehicle might influence the cost or extent of distributing instruction, but only the content of the vehicle can influence achievement. (p. 445)

Some of our own research supports Clark’s claims. We (Hasselbring et al., 1987–1988) conducted a study that compared the use of an overhead projector and a videodisc to present material, with content controlled for. Both groups received
direct instruction on fraction and fraction computations using a procedurally oriented approach. The same teacher taught both groups and used the same instructional sequence, which was presented by videodisc to one group and by overhead projector and transparencies to the other. Consistent with Clark's (1983) analysis, the group taught with transparencies displayed on an overhead projector did no better than the group taught with a videodisc, although both did better than two groups taught using the traditional classroom curriculum and methods. However, using the videodisc was definitely easier than handling a huge stack of transparencies, and the same information was covered in less time using the videodisc. The distressing part of this research was that even though two experimental groups did well on a criterion-referenced test over the fractions information, when asked to apply this knowledge to real-life problems, they were unable to do so. Findings such as these have motivated many educators to seek alternatives to transmission models of learning and instruction. These are discussed later, under constructivist models of learning.

Research on Computer Programming

Research on computers also included a great deal of interest in teaching computer programming and in the effects this might have on students' thinking (Dalby & Linn, 1985; Linn, 1985). Salomon (1992) provides an excellent discussion of this work. For example, he notes that the goal of helping students become "computer literate" was translated into teaching programming. Luehrmann (1972, cited in Salomon, 1992) stated: "If the computer is so powerful a resource that it can be programmed to simulate the instructional process, shouldn't we be teaching our students mastery of this intellectually powerful tool?" (p. 77).

Early efforts to teach programming focused primarily on BASIC (Beginners All-purpose Symbolic Instruction Code). The emphasis was primarily on languages such as BASIC as curricula to be learned. The publication of Papert's _Mindstorms: Children, Computers, and Powerful Ideas_ in 1980 generated a great deal of interest in Logo programming and its potential cognitive benefits. Furthermore, Papert's vision for teaching LOGO was dramatically different from teaching methods consistent with transmission models (cf. Harel & Papert, 1991). We discuss research on Logo programming later, under constructivist models of learning.

Research on Distance Learning

Very early work on distance learning focused on the effects of one-way instructional television (Chu & Schramm, 1967; Schramm, 1977; Whittington, 1987). Later work included the use of one-way video with two-way audio systems (Cookson, 1989; Moore, 1989). Russell (1993) discusses numerous studies that demonstrate that students learn as well with distance technology as their counterparts who receive on-campus, face-to-face instruction (see also Shavelson, Webb, & Hotta, 1987). It is important to note that most of the early uses of distance learning technologies were based on the transmission model, and most addressed traditional instructional goals.

More recent studies have attempted to compare the effectiveness of different types of distance learning technologies with one another as well as with face-to-face instruction (Beare, 1989; Galvin, 1987; Learmont, 1990; Martin & Rainey, 1993; Pugh, Parchman, & Simpson, 1992; Ritchie & Newby, 1989; Schlosser & Anderson, 1994; J. B. Smith, 1993). Consistent with Clark's argument, these experiments and evaluations found little difference between the effectiveness of delivery systems (Clark, 1983; Clark, 1989). These studies indicate the need to investigate the effects of different instructional designs rather than the effectiveness of various technologies as the means to deliver or transmit content to learners.

Migration from Laboratories to Classrooms and Connected Classrooms

The LTC framework includes an emphasis on research settings—laboratory, classrooms, connected classrooms—because different issues arise as researchers move from one setting to another. For example, as one moves from laboratory to classroom settings, a simple but extremely important question arises: Where does one find the time in the day for students to work on computer-based applications? Because the time available in a school day is limited, this question is by no means trivial.

In general, technology applications that are consistent with transmission models of learning (cells 1, 2, and 3) are easier to move into classroom settings than are applications consistent with constructivist models. The reason is that most classrooms are consistent with transmission models of learning; hence applications consistent with these models can simply be assimilated into existing classroom practice. When we discuss constructivist models later in the chapter, we will see many more challenges involved in moving from laboratory contexts to real classrooms in real schools.

The use of ILS in a school computer laboratory setting (cell 2) is a particularly clear example of ease of assimilation. Under this model, classroom teachers do not need additional expertise in technology; they can simply send their students to the school's computer laboratory. It is much easier to train one laboratory technician per school than to train every teacher in a school. Similarly, the use of one-way distance learning technologies (cell 3) does not require much change in traditional classroom practice.

Summary

Overall, the results of early research on CAI suggested that it sometimes produced results that were superior to traditional classroom instruction. However, Clark's arguments about the confounds of the research conducted cannot be ignored. Equally important is a consideration of the kind of instruction and assumptions about learning made by the majority of CAI programs prior to 1990. In most cases, the technology was used to deliver instruction more efficiently and was consistent with a teaching-is-telling approach. Likewise, traditional approaches to assessment and evaluation of student performance were based on the same set of assumptions. Most present-day ILSs carry on in this tradition (see Means et al., 1993, for some exceptions).

Early research on the effects of computer programming treated the area as a curriculum to be transmitted rather than as a tool to be used to accomplish goals established by students.
and teachers (Mayer, 1988b; Salomon, 1992). Research on distance learning was also driven by a transmission model of learning and teaching. Its effects were compared with the achievement of students in traditional classrooms where the teacher was present rather than at a remote site.

Since applications based on transmission models are consistent with existing practice in most classrooms, migrations from laboratory to school contexts were relatively smooth. In contrast, migrations are much more challenging when the theory of learning underlying the application requires a transformation of existing classroom practice.

THEORY AND RESEARCH RELEVANT TO CONSTRUCTIVIST MODELS OF LEARNING

This section explores shifts in thinking about learning and education that have taken place in the past 15 to 20 years, and how these shifts have shaped the design, implementation, and study of technology-based applications. In the context of the LTC framework, these changes involve a shift from the first row of the framework (programs based on transmission models of learning) to the second and third rows (programs based on constructivist models of learning). In this section we discuss the second row (cells 4, 5, and 6) of the LTC framework, or constructivist-based applications that transform part, but not all, of the school day. The third row of the LTC framework is discussed in the next section.

The Need for Change in the Goals of Education

In 1983, the authors of A Nation at Risk called attention to the serious problems of schooling in the United States by describing the nation's efforts as "an act of unthinking, unilateral educational disarmament" (National Commission on Excellence in Education, 1983). Spurred by the report, politicians, business leaders, and educators sounded the call for educational reform (e.g., Wise, 1989).

A number of theorists have attempted to better define the nature of the educational crisis identified in A Nation at Risk and expressed by so many others (e.g., Resnick, 1987a). As Bruer (1993) suggests: "Consistently, the assessments show that the educational crisis is not one of decline; it is one of stagnation" (p. 2). The major problem is that schools have not kept pace with society's expectations and needs for the rapidly changing world of the 21st century (see also Berryman, 1993; Reich, 1993; U.S. Department of Labor, 1992).

The idea of preparing people for a rapidly changing world is a daunting new challenge. Rapid change requires lifelong learning, and this means that people who enter the work force must be prepared to learn on their own. Resnick (1987a) cites a number of ways in which schools have failed to prepare students for lifelong learning:

Employers today complain that they cannot count on schools and colleges to produce young people who can move easily into more complex kinds of work. They seem to be seeking general skills such as the ability to write and speak effectively, the ability to learn easily on the job, the ability to use quantitative skills needed to apply various tools of production and management, the ability to read complex materials, and the ability to build and evaluate arguments. These abilities go well beyond the routinized skills of the old mass curriculum. (pp. 6–7)

Resnick emphasizes that the skills required for effective work following high school graduation are now essentially equivalent to those that were required for college-bound students in the 1980s. She states: "It is a new challenge to develop educational programs that assume that all individuals, not just an elite, can become competent thinkers" (Resnick, 1987a, p. 7).

New Visions of Human Potential and Human Learning

The ability to achieve genuine and dramatic change requires new visions of human learning and human potential. Ideas about learning have been strongly influenced by theoretical developments that have accompanied the cognitive revolution in psychology. Several authors (e.g., Gardner, 1985; Resnick & Klopfer, 1989) provide excellent descriptions of this revolution. One major shift is in the view of learning. Instead of knowledge being viewed as something to be received, accumulated, and stored, it is viewed as being actively constructed by organisms through interaction with their physical and social environments and through the reorganization of their own mental structures (e.g., Cobb, 1994; Cobb, et al., 1992; Collins, 1991a; Greeno, Smith, & Moore, 1993; Harel & Papert, 1991; Papert, 1980; Savery & Duffy, in press; see also chapters 2 and 16). A second major shift has been in a realization of the importance of social contexts for learning. In chapter 16, De Corte and co-authors argue that social considerations are part of the second wave of the cognitive revolution. During the first wave, the primary focus was on individual thinkers and learners, with a deemphasis on affect, context, culture, and history (Gardner, 1985). During the second wave, theorists have attempted to relocate cognitive functioning within its social, cultural, and historical contexts (e.g., Bransford et al., 1991; J. S. Brown, Collins, & Duguid, 1989; Duffy & Jonassen, 1992; Duffy et al., 1993; Padilla, 1991; Pea, 1993a, 1993b; von Glasersfeld, 1989; Wheatley, 1993, chapter 2).

Taken together, the two phases of the cognitive revolution have led to important changes in thinking about ways to assess and facilitate human intelligence and development.

Changing Views of Intelligence. In conjunction with new views of human learning are new visions of human potential and how we might assess it. An important change in thinking involves the concept of human intelligence. Almost a century ago, Binet (Binet & Simon, 1908) developed an assessment instrument whose purpose was to predict school success. And it did that well (see Kail & Pellegrino, 1985, for discussion). Unfortunately, the intelligence test came to define what it meant to be intelligent in general rather than what it meant to be intelligent in an academic sense.

There have been a number of efforts to broaden the concept of intelligence to encompass more and varied kinds of thinking. Neisser (1976) argued that the concept of academic intelligence needed to be supplemented with another concept that he called "practical intelligence" and defined as "intelligent performance in practical settings." Differences between academic and practi-
tical intelligence capture the difference between individuals who seem "book smart" but who do not function well in the everyday world. Of course, some individuals do well in both domains. The book Practical Intelligence (Stemmerg & Wagner, 1986) contains a number of articles that provide evidence of the value of the concept of practical intelligence.

Another criticism of traditional concepts of intelligence is that they overemphasize verbally loaded skills. Gardner (1983) argued persuasively for broadening the concept of intelligence to make room for multiple intelligences, including musical, spatial, and so forth. Expanded views of intelligence are especially important because people's beliefs about the nature of intelligence can affect their assessment of their own capabilities and their actual performance. For example, in studying task performance, Bandura and Dweck (1985; cited in Cain & Dweck, 1989) found that children who believed that intelligence was incremental tended to emphasize developing their skills and improving their abilities. However, children who held an entity view of intelligence were oriented toward demonstrating how smart they were and reacted to the task as a test of ability. In the face of failure, incremental views tended to be associated with "mastery" orientations, whereas entity views tended to be associated with "helplessness" responses (Cain & Dweck, 1989; Dweck, 1989).

Researchers have also argued for the importance of a concept of "distributed intelligence" (e.g., A. L. Brown & Campione, 1990; Hutchins, 1983; Pea, 1993b, 1994; Pea & Gomez, 1992; Salomon, 1993b; Salomon et al., 1991). Rather than being viewed as existing in individual minds, intelligence is viewed as a property of groups of individuals who collaborate to achieve shared goals. The concept of distributed intelligence has important implications for issues of curriculum, instruction and assessment. (See Salomon, 1993a, for an edited volume concerned with the implications of distributed cognition.)

Explorations of the Nature of Expertise. An alternative to equating thinking with intelligence as measured by intelligence tests is to examine the characteristics of individuals who are among the very best thinkers in their fields. Classic work on the nature of expertise and expert thinking focused on the area of chess (e.g., Chase & Simon, 1973; deGroot, 1965). Since then, researchers have begun to study the nature and development of expertise in a variety of other areas, including physics, mathematics, computer programming, writing, social studies, and teaching (e.g., Berliner, 1991; Bransford, Sherwood, Vye, & Rieser, 1986; Carter, Cushing, Sabers, Stein, & Berliner, 1988; Chi, Feltovich, & Glaser, 1981; Chi, Glaser, & Farr, 1988; Chi, Glaser, & Reese, 1982; Glaser, 1986, 1991; Hayes, 1990; Larkin, McDermott, D. P. Simon, & H. A. Simon, 1980; Lesgold, 1988; Sabers, Cushing, & Berliner, 1991). A major conclusion from the research is that high-level expertise requires a great deal of domain-specific knowledge. Experts do not simply have more knowledge about an area than novices, they also seem to have organized that knowledge in ways that are qualitatively different. Like the concept of intelligence, the idea of individual expertise has been augmented by a concept of distributed expertise (e.g., A. L. Brown & Campione, 1990; Hutchins, 1983; Pea, 1993b, 1994; Pea & Gomez, 1992; Salomon, 1993b; Salomon et al., 1991).

Learning in Everyday Settings. Insights from the work on practical intelligence and the nature of expert performance have been enhanced by work on the learning and problem solving of children and adults performing everyday tasks in everyday settings, such as getting around their house or shopping in a grocery store (e.g., Bransford & Heldmeyer, 1983; T. N. Carraher, D. W. Carraher, & Schliemann, 1985; Lave, 1988; Lave & Wenger, 1991; Nunes, Schliemann, & D. W. Carraher, 1993; Resnick, 1987b; Rogoff, 1990; Rogoff & Lave, 1984; Saxe, 1988; Schliemann & Acioly, 1989). It has become clear that many aspects of everyday cognition differ from the more formal processes emphasized in school and tested on tests. The picture from research on learning in everyday settings is that humans are much more adaptable than one would have imagined from traditional curricula and traditional tests (e.g., CTGV, 1993a; Lave & Wenger, 1991).

Research on Early Competencies. Research on the nature of expertise and everyday cognition has been accompanied by a correlative change in conceptions of children's thinking. Increasingly greater emphasis is being placed on the importance of the physical and social context in which thinking occurs and on the interaction of the individual with the objects and events in the environment (Carey, 1985; Donaldson, 1979; Driver, Guesne, & Tiberghien, 1985; Greer, 1994; Lave, 1992, 1993a; L. B. Smith, Sera, & Gattuso, 1988; Wheatley, 1993).

Within appropriate physical and social contexts, "early competencies" have been observed in young children's number, communication, problem-solving, and search behavior (Gelman & Gallistel, 1978; Gelman, Meck, & Merkin, 1986; Klahr, 1978; Shatz, 1982; Wellman & Somerville, 1982). These competencies may profitably be understood in terms of the performances afforded or enabled by the environment. For example, a number of elements have to be properly aligned in order for children's competencies to reveal themselves: The context of the task must be familiar to the children, the amount of information must not exceed their working memory capacity, constraints on the materials may encourage certain behaviors and prevent others, and so forth (e.g., Case, 1985; Klahr, 1978; Siegler, 1978). Even analogical transfer and learning-to-learn competencies can be demonstrated in preschoolers under the appropriate scaffolding circumstances (A. L. Brown & Kane, 1988; A. L. Brown, Kane, & Echols, 1986; A. L. Brown, Kane, & Long, 1989).

Research on Motivation. Researchers have also begun to clarify the roles of motivation and interest in human learning. Early research on motivation was consistent with transmission models that focused on delivering instruction. As it was delivered, researchers asked about the kinds of consequences (rewards) that might motivate students to continue with the learning task. For example, programs designed to teach math facts might follow a correct answer with a "correct" or with an elaborate set of consequences (e.g., getting to continue with a search through a maze). Several papers describe the results of this type of research (e.g., Lepper, 1985; Lepper & Chabay, 1985; Lepper & Malone, 1987; Parker & Lepper, 1992).

In recent years, there have been new approaches to the study of motivation. For example, Collins (1996) discusses differences between approaches that attempt to make learning fun through
fantasy and elaborate reinforcements and those that attempt to enhance motivation by focusing on authentic tasks that students perceive as real work for real audiences. Several investigators report that students are very interested in tasks that, despite requiring a lot of work, are perceived by them as authentic (e.g., Blumenfeld et al., 1991; Bransford et al., in press; A. L. Brown & Campione, 1994; Collins, Hawkins, & Carver, 1991; CTGV, 1992d, 1993b, 1994b; S. R. Goldman et al., in press; Hickey et al., 1993; Lamon et al., in press; Scardamalia, Bereiter, & Lamon, 1994; Sharp et al., 1992a, 1992b).

An emphasis on motivation based on authentic tasks is one example of a promising theoretical shift away from a generalized concept of motivation and interest toward context-specific constructs. For example, Paris and Turner (1994; Paris & Brynes, 1989) have introduced the term *situated motivation* to describe new socioconstructivist conceptualizations of motivation in relation to the particular topic and setting within which motivation is tested. (See Renninger, Hidi, and Krapp [1992] for similar approaches to interest.) Consistent with this approach, motivation researchers are increasingly using descriptive research methods more typical of socioconstructivist research (e.g., McCaslin, 1993; Meece, 1991; Pintrich & DeGroot, 1993; Turner, 1992).

Research by McCombs (1991, 1994) is also highly relevant to constructivist models of learning and instruction. She conceptualizes motivation for lifelong learning as “a natural response to learning opportunities that is the result of three elements: (1) self-constructed evaluations of the meaning and relevance of a particular learning opportunity relative to one’s personal interests, needs and goals; (2) an understanding of one’s agency and capacities for self-regulation; and (3) contextual conditions that support perceptions of meaningfulness and self-determination, including supportive personal relationships” (1994, pp. 5–6).

An important point about situations that motivate people is the idea that motivation frequently involves a combination of intrinsic and extrinsic factors. For example, in analyzing factors that influence activities in our technology center (B. Barron et al., in press), it became clear to us that, although intrinsic motivation is extremely important, extrinsic motivation in the form of outside challenges and deadlines also plays an extremely important role. In our Jasper Challenge Series we have tried to create conditions in schools that successfully bring both intrinsic and extrinsic motivational factors into play (e.g., B. Barron et al., in press; CTGV, 1994a, in press; S. R. Goldman et al., 1994).

**Summary of New Visions of Learners and Learning.** Overall, research with children, as well as with adult learners acquiring expertise in a particular field, suggests that the development of thinking is limited more by lack of knowledge than by the absence of general logical capacities. One important implication of this finding is that thinking can and should be part of the curriculum from the earliest grades (e.g., Resnick & Klopfer, 1989). A second implication is that traditional modes of assessment, such as intelligence tests, fail to provide an accurate picture of human potential and adaptability (e.g., Ceci & Ruiz, 1993; S. R. Goldman & Pellegrino, 1991). The fact that knowledge and experience play such important roles in thinking also suggests that we should expect significant individual differences in development and hence in readiness for various types of learning. This argues against “assembly line” schooling where the approach is to instill the same knowledge in each child at the same point in time.

**New Visions of Curriculum, Instruction, and Assessment**

New conceptions of human learning and human potential have important implications for curriculum, instruction, and assessment (e.g., Bereiter, 1994; Bransford et al., 1991; Brue, 1993; Perkins, 1992; Resnick, 1987a; Savery & Duffy, in press). One problem with traditional approaches has been called the “inert knowledge” problem (Whitehead, 1929). Students in traditional classrooms are often able to retrieve specific facts and skills when explicitly prompted to do so. However, they often fail to use potentially relevant knowledge when asked to solve open-ended problems (e.g., Bransford, Franks, Vye, & Sherwood, 1989; Hasselbring et al., 1991). In Whitehead’s terms, their knowledge remains inert. Attempts to help students develop usable knowledge require simultaneous changes in curriculum, instruction, and assessment. Each of these areas is discussed below.

**Changes in Curriculum.** Many theorists have begun to search for approaches to curriculum that provide opportunities for sustained thinking about authentic problems that form the basis of authentic inquiry in domains such as science, social studies, and mathematics (e.g., CTGV, 1990; Honebein, Duffy, & Fishman, 1993; Kinzer, Gabella, & Rieth, 1994; Pea, 1993a). This means that materials that attempt to provide a breadth of factual coverage must be replaced by, or supplemented by, ones that involve opportunities for in-depth exploration. As A. L. Brown and colleagues (A. L. Brown et al., 1993) argue, existing curricular guidelines of the scope-and-sequence variety are insufficient. These guidelines, often correlated with standardized test questions, result in disjointed survey courses.

Alternatives to disjointed survey courses include curricula that emphasize case-based and problem-based learning. Results from a number of studies suggest that these approaches are motivating and more likely to produce transfer in complex problem-solving tasks than are fact-based survey courses (e.g., Barrows, 1985; Bransford & Stein, 1993; Clancy & Linn, 1992; CTGV, 1992a, 1992d, 1993b; Duffy, in press; Elstein, Shulman, & Sprafka, 1978; Hmelo, 1994; Hmelo, Gotterer, & Bransford, 1994; Lyon et al., 1991; Mandl & Gras, 1993; Norman & Schmidt, 1992; Patel & Groen, 1986; Patel, Groen, & Norman, 1993; Schank, Linn, & Clancy, 1993; Schmidt, 1993; Williams, 1992, 1994). Others report similar results when using project-based curricula where students create products (reports, multimedia documents) based on questions they have generated (e.g., A. L. Brown & Campione, 1994; A. L. Brown et al., 1991; Carver, Lehrer, Connell, & Erickson, 1992; Collins et al., 1991). Several authors report that transfer can be enhanced by beginning with concrete, problem-based curricula (where problems are presented to students in the form of verbal or visual cases) and then proceeding to more student-generated projects that build on the ideas presented in the problem-based curricula (e.g., CTGV, 1994a; Williams, 1994). In addition, data suggest that flexibility of transfer is enhanced when students are...
prompted to revisit cases from a "what if" perspective (e.g., "What if this part of the problem were changed?") and asked to explore the implications of the change (e.g., CTGV, 1993b; Williams, 1994).

Changes in Instruction. Curricula that emphasize sustained thinking also require a change in the instructional climate of typical classrooms. In most classrooms, students adopt the role of receivers of information that is dispensed by teachers, textbooks, and other media (A. L. Brown, 1992; Means, 1994). The role of the teacher is to deliver information and manage learning. Usually, everyone is taught the same thing at the same time.

In constructivist classrooms, students are usually provided with opportunities to plan and organize their own research and problem solving, plus opportunities to work collaboratively to achieve important goals (e.g., Blumenfeld et al., 1991; A. L. Brown & Campione, 1994; A. L. Brown et al., 1993; Carver et al., 1992; CTGV, 1994a; Collins et al., 1991; Lamon et al., in press; Linn & Clancy, 1992; Savery & Duffy, in press). In addition, many constructivist classrooms are consistent with an emphasis on the importance of distributed expertise (e.g., B. Barron et al., 1995; A. L. Brown et al., 1993; Pea, 1993b, 1994). Students are allowed to specialize in particular areas so that the community can capitalize on diversity. An emphasis on distributed expertise is distinctively different from environments in which all students are asked to learn the same things at the same points in time.

Mitchell Nathan and Sashank Varma provide the following analysis of information flow in transmission versus constructivist classrooms. In transmission models the information flow goes exclusively from teacher (T) to each of the students (S1, S2, ..., Sn). The flow of question and discussion is exclusively from each student to the teacher. For n students, the number of connects is simply n for either information flow or questions/discussions. In contrast, in the constructivist classroom information flow and the flow of questions/discussions occur among all members of the group (teacher and students). In the maximally connected graph containing n students and one teacher (i.e., n + 1 = m members or nodes), the number of links is (m − 1) + (m − 2) + ⋯ + 1, which equals (m(m − 1))/2. For 30 students and one teacher this is 465 lines of communications (which operate both ways). In comparison, only 30 lines exist in the transmission model. Obviously, the transmission model represents a highly restricted form of communication.

Changes in Assessment. A focus on curriculum and instruction inevitably leads to the issue of assessment. What is measured and how is the information used? During the 1980s there was a great deal of discussion of the need for standardized forms of assessment and how they worked against the development of curricula for improving content-relevant thinking skills. Major criticisms have been raised against standardized testing, in part because of the lack of high stakes and in part because of the kinds of competencies that they test. (See Gifford and O'Connor [1991] for various perspectives on changes in assessment.)

Although there is wide consensus on the problems created by the testing movement, most researchers do not take the view that testing ought to be eliminated. As Fredericksen and Collins (1989) emphasize:

Such an approach, however, would deny to the educational system the ability to capitalize on one of its greatest strengths to invent, modify, and in other ways improve instruction as a result of experience. No school should be enjoined from modifying its practices in response to their perceived success or failure. (p. 28)

The problem, according to these authors, is not that teachers teach to the test. Instead, the problem is the type of instruction that is engendered by standardized tests. Many teachers are teaching concepts and procedures in a superficial way. Schoenfeld (1991) described an extreme case in which the structure of the test items on a state-administered geometry test was such that students who had been taught to rote memorize geometric proofs performed best. The test did not require students to justify the steps in their constructions and thereby demonstrate their mathematical reasoning abilities. It merely required that their constructions contain all of the arcs and lines and that they be accurately drawn.

Researchers (Frederiksen & Collins, 1989; Pellegrino, 1991; Quellmalz, 1985) have suggested that we need to change the types of tests that we use to assess educational outcomes in order to prevent the kind of abuse described above. Standardized tests mostly emphasize low-level skills, factual knowledge, and memorization of procedures. Frederiksen and Collins (1989) propose that we endeavor to develop direct tests—others use the term "performance-based assessments"—of students' thinking. Direct tests attempt to evaluate students' performance on high-level cognitive tasks over an extended period of time (e.g., Lesgold, Eggen, Katz, & Rao, 1992). For example, the task might involve writing a piece of persuasive text or conducting a scientific experiment (e.g., Eylon & Linn, in press; Linn & Clark, in press).

Even performance assessments do not ensure that students are developing the foundations for lifelong learning. Lin et al. (in press) argue that most assessments of transfer are static tests; people learn something and then receive a set of transfer problems (e.g., M. Gick & K. Holyoak, 1980; M. L. Gick & K. J. Holyoak, 1983) or perform a specific task. Scores on such problems can be increased by "teaching to the test," which explicitly includes "teaching for transfer." However, high scores on a specific, static transfer test do not guarantee that students have learned to learn on their own. Assessments of learning to learn require tests of dynamic transfer. A. L. Brown, Bransford, Ferrara, and Campione (1985) discuss a situation in which a learner did very poorly on tests of static transfer yet was able to demonstrate a rich variety of learning-to-learn skills when given a dynamic test that provided the opportunity to access resources that could help him learn to solve problems that he needed to solve.

Linking Curriculum, Instruction, and Assessment. The ways in which curriculum, instruction, and assessment are linked reflect the overall climate or community of the classroom. In constructivist classrooms, students working on problem-based and project-based curricula often uncover issues that exceed the immediate expertise of the teacher (e.g., B. Barron et al., 1995; A. L. Brown & Campione, 1994). Therefore, teachers as well as students must be learners. Instructional strategies involve a focus on ways to help students take responsibility for their own learning rather than on ways for teachers or technol-
ogy to deliver instruction. Assessment is formative and is designed to encourage reflection and subsequent improvement both by students and by teachers (e.g., B. Barron et al., 1995; CTGV, in press; S. R. Goldman et al., 1994). Connections with groups outside the classroom provide opportunities for authentic audiences who can help teachers and students work together to meet outside goals. In the process, students and teachers are also helped to reflect on their thinking and revise their work (e.g., B. Barron et al., 1995; A. L. Brown & Campione, 1994; Scardamalia et al., 1994).

Technology Research Relevant to Constructivist Models of Learning

The preceding discussion suggested new visions of what classrooms might look like. Technology can support these new visions, but it can support traditional ones as well (e.g., Jones, Valdez, Nowakowski, & Rasmussen, 1994; Newman, 1992b). In this section we discuss technology-based applications that are consistent with constructivist models of learning. We focus on applications designed to transform only part of the school day (cells 4, 5, and 6 of the LTC framework). Attempts to transform all of schooling (cells 7, 8, and 9) are discussed in the next section.

Types of Technology Applications. Our discussion in this section is organized around four categories of educational technology that were used in an excellent review by Means et al. (1993): tutorials, exploratory environments, applications (tools), and communication. We also add a fifth category, teaching programming, as a particular type of exploratory environment. For each category we discuss how technology programs that fit classrooms consistent with constructivist models of learning (cells 4, 5, and 6) differ from those that fit classrooms operating according to transmission theories (cells 1, 2, and 3).

Tutorial Environments. Earlier we noted that the learning systems developed in the 1960s and 1970s were consistent with transmission models of instruction (cells 1, 2, and 3 in the LTC framework). Whether they were IILs or stand-alone programs, these systems were usually designed to help students acquire discrete sets of facts and skills. Assessment was based on student performance on these facts and skills.

New versions of tutorial programs have changed along a number of dimensions that fit constructivist models of learning. An especially important one is the nature of the information that students are asked to acquire. In geometry, for example, computer tutorial systems can help students memorize facts about points, lines, the measurement of angles, and so forth. The acquisition of these kinds of facts is consistent with research in row 1 of the LTC framework.

In contrast, systems such as those developed by John Anderson, Ken Koedinger, and their colleagues (Anderson, 1987; Anderson et al., 1985; Koedinger & Anderson, 1990, 1993) are designed to support the process of geometric reasoning. For example, in the original Geometry Tutor, Anderson and colleagues provided explicit support for search through the space of theorems and axioms that were expected to connect the "given" statements to the "goal" statements (Anderson et al., 1985). In later versions of geometry tutors such as ANGLE, support included the development of diagram configurations (visual cases, which are essentially pieces of common diagrams) that research indicated were useful to expert geometers across a wide variety of problems. Overall, tutorial systems designed to support students' reasoning are very different from ones designed to help students memorize sets of discrete facts (e.g., the definitions of a point and a line) and skills (e.g., how to measure angles).

It is noteworthy that the tutorial programs developed by Anderson, Koedinger, and colleagues are based on an elaborate cognitive model of the user. An important aspect of their model-tracing paradigm is that the process data these systems can collect are very informative. For example, they are a projection of a student's process onto the prerecorded paths of experts or of prior students' misconceptions. In general, student modeling approaches to building tutoring systems are very different from simply recording the accuracy of student responses and providing feedback such as "right" or "wrong" (e.g., Anderson, Corbett, Fincham, Hoffman, & Pelletier, 1992). Derry and Lajoie (1993) provide insightful discussions of the roles of student models in computer design. Other examples of student modeling systems can be found in Lajoie and Derry (1993a).

Interestingly, another strategy for building tutors that enhance understanding (rather than the mere memorization of facts or procedural skills) is to provide information that can inform the reflection of the humans who use the programs. Developers of so-called "unintelligent" systems have adopted this strategy (e.g., Derry & Lajoie, 1993; Nathan, 1990; Reusser, 1993). For example, students can be provided with computer simulations that show the implications of their problem solving, and these simulations can allow users to reflect on and refine their own thinking (CTGV, 1994a; Nathan, Kintsch, & Young, 1992). Similarly, tutorial environments can provide methods for scaffolding users' reflections on the problem-solving processes and their experiences with the system (Katz & Lesgold, 1993; Lajoie, 1993; Lesgold, Lajoie, Bunzo, & Eggen, 1992; Lin, 1993). These have been shown to facilitate transfer to subsequent tasks (Lin, 1993; Nathan et al., 1992).

An interesting variation on tutorial environments is provided by Hunt and Minstrell (1994). They have developed a computer-based "diagnoser" that captures students' thinking about key ideas in physics. Through the use of the diagnoser, the instructor is able to assign students problems that help them change their preconceptions and develop new theoretical points of view.

Exploratory Environments. Exploratory environments allow students to direct their own learning through discovery or guided discovery processes. They are environments in which students construct their own knowledge, usually in the context of complex problems or situations. Therefore, they are particularly appropriate to the second row of the LTC framework and its concern for constructivist classroom settings.

An excellent illustration of an exploratory computer environment is the Geometric Supposer, developed by Schwartz, Yerushalmy, and colleagues (Yerushalmy, 1991; Yerushalmy, Cha- zan, & Gordon, 1990). It is a powerful environment for making and proving conjectures in geometry. Another dynamic geometry microworld is the Geometer's Sketchpad (Jackiw, 1991). Users can construct and manipulate geometric figures to investi-
gate geometric relationships. Research suggests that both geometry environments require teacher guidance to function well (e.g., Yerushalmi, 1991; Yerushalmi et al., 1990; Wiske, 1990). In the science area, Linn and colleagues (Friedler, Nachmias, & Linn, 1990; Linn, 1992) have developed the Computer as Lab Partner (CLP) curriculum for heat and thermodynamics. Students formulate and design experiments, predict the outcomes and explain the predictions, conduct the experiment, reconcile the results, with their predictions, and interpret the results (Linn & Songer, 1991; Songer & Linn, 1991; see also chapter 15). The computer provides simulations and a laboratory notebook for recording the information, thereby scaffolding student understanding.

A more general application for allowing students to explore systems is STELLA (Structural Thinking Experiential Laboratory with Animation) and the hypercard version STELLAStack (Richmond, 1985, 1993; Richmond & Peterson, 1988, 1990). These modeling and simulation applications permit students to build and observe the operation of dynamic systems. STELLA and STELLAStack are important components of the STACI project (Mandinach & Cline, 1994). STACI has been concerned with implementing systems thinking in classroom instruction in history, science, and mathematics. Consistent with constructivist philosophy, systems thinking is a problem-solving strategy for examining the dynamic relationships among the parts of a phenomenon. Systems thinking often emphasizes change over time. STELLA has been a primary mechanism for introducing systems thinking into the classroom culture (Mandinach & Cline, 1994).

The development of computer-based microworlds provides additional examples of exploratory environments. Examples include Smitytown, an economics microworld (Shute, 1993; Shute & Glaser, 1991); ThinkerTools, a world of Newtonian principles of mechanics (White, 1993); Boxer, an environment in which students create their own computational representations of content areas such as physics (disessa, 1993); and 4MChem, a system for exploring chemical equilibrium (Kozima, Russel, T. Jones, Marx, & Davis, 1993). Software such as Sim City and Rocky’s Boots has also been used as a basis for exploratory projects in school (e.g., Bransford & Stein, 1993; Delclos & Kulewicz, 1986). Pogrow (1990a, 1990b) has made ingenious use of computers and computer software as objects that students want to learn about. Students develop reading, comprehension, and problem-solving skills as they consult manuals and collaborate to achieve their learning goals.

Video and multimedia environments have also been used to create exploratory contexts. Programs such as Palenque (Wilson, 1987), Voyage of the Mimi (Bank Street College of Education, 1984), The Adventures of Jasper Woodbury (CTGV, 1990, 1991, 1992a, 1992c, 1993b; Zech et al., 1994), the Young Children’s Literary Series (e.g., Bransford et al., in press; Brophy et al., 1994; Sharp et al., 1992a, 1992b); the Young Sherlock Project (e.g., Bransford et al., 1988; Bransford, Vye, Kinzer, & Risko, 1990; CTGV, 1990; Kinzer, Williams, & Cunningham, 1992; McLarty et al., 1990), Scientists in Action (CTGV, 1992b; S. R. Goldman et al., in press; Sherwood et al., in press), the Adult Literacy Project (CTGV, 1992a), The Great Space Race (Tom Snyder Productions, 1992), and The Math Mystery Series (Human Relations Media, 1992) are all examples of complex, authentic situations in which students use content in mathemetics, science, and social sciences to solve problems. Software extensions to these programs provide additional kinds of learning support.

Interactive multimedia systems such as the ASK systems (Ferguson, Bares, Birnbaum, & Osgood, 1992), Rain Forest (National Geographic, 1991), and software relevant to modeling ecosystems (Jackson, Stratford, Guzdial, Krajcik, & Soloway 1995) allow the learner to explore various topics from multiple perspectives (see also Spiro & Jehng, 1990; Spiro et al., 1987). Interactive CD products such as Treasures of the Smithsonian (Hoekema, 1993) also create potentially rich environments for students to take control of their learning.

A danger in some of the emerging multimedia systems is that they do not engage the learner in active processing and restructuring of information. In some cases there is little opportunity for students to directly explore and manipulate the models that underlie various simulations. Other uses of multimedia function more as "encyclopedias" than as environments in which problems can be posed or solved (CTGV, 1993c). Of particular importance are multimedia resources that allow students to create their own multimedia products that they can show to others. Examples of these kinds of activities include the Thinking Skills Project (Reeves & Hamm 1993), the Discover Greater Project (Carver et al., 1992; Collins et al., 1991; the Young Children’s Literacy Project (Brophy et al., 1994), and the High School Literacy Project (CTGV, 1994b).

Important issues for pedagogy and assessment arise in the context of exploratory environments. Much of the activity in exploratory environments occurs in small groups because students deal with authentic problems that are quite complex. Working on them together facilitates problem solving and capitalizes on distributed expertise (e.g., Barron, 1991; A. L. Brown et al., 1993; CTGV, 1992c, 1993b, 1994a; Yackel, Cobb, & Wood, 1991). However, not all collaborations work effectively (S. R. Goldman, Cosden, & Hine, 1992; Linn & Burbules, 1993; Salomon & Globalberson, 1989). Procedures for “making students thinking visible” provide opportunities for formative assessments that can be used to optimize learning (B. Barron et al., 1995; CTGV, 1994a).

Teaching Computer Programming. We noted in our earlier discussion of transmission models of learning that early efforts to teach programming tended to focus on programming languages such as BASIC as a curriculum to be learned. Papert’s Mindstorms (1980) suggested a vision for teaching programming that makes it into an exploratory environment. Papert argued that, with an appropriately structured language such as LOGO, students would not simply learn to program a computer. They would also discover how to think and learn for themselves. LOGO was designed to provide an exciting environment that had no ceiling and no floor (i.e., that could be used by people who varied from young children to advanced programmers).

Early attempts to assess the cognitive effects of LOGO programming found few cognitive benefits (e.g., Pea & Kurland, 1984). Subsequent studies (see Mayer, 1988b) found cognitive benefits (e.g., better planning), but they required changing the instruction that surrounded LOGO in order to achieve these effects. For example, Littlefield and colleagues (Littlefield et al., 1988) noted that most of the early studies of LOGO had failed to include an assessment of how well students had learned.
LOGO programming in the first place. When this was assessed, students' knowledge of LOGO was often found to be weak. Littlefield and colleagues noted that, if there is only a modest amount of initial learning, there is little reason to expect any transfer to new tasks.

Many researchers began to design instruction around LOGO that encouraged students to become more planful and take a design stance toward their programming. Without this type of instruction, students' behavior during LOGO programming often fits a pattern of trial and error (Carver, 1988; Hawkins, 1987b; Littlefield et al., 1988). As LOGO began to be taught as a means to other ends (to the acquisition of planning skills, knowledge of geometry, and so forth), cognitive benefits on transfer tests began to show up (e.g., Lehrer, Guckenber, & Lee, 1988; Lehrer, Lee, & Jeong, 1994; Lehrer, Randle, & Sancilio, 1989).

Salomon (1992) points out that research on LOGO suffers from an interesting paradox. He argues that LOGO taught according to the original vision of Papert (1980) fared poorly in tests of cognitive benefits. However, as uses of LOGO strayed from the original vision, the results began to look more favorable. Salomon believes that LOGO and other programming languages are more successful when they become viewed as tools to help students achieve more specific goals, such as learning to create efficient designs or learning key principles of geometry. We discuss additional computer tools for learning in the section below.

We agree with Salomon's analysis of the evolution of attempts to teach LOGO. We add that, after viewing several tapes of Papert in LOGO classrooms, it seemed to us that Papert was an outstanding teacher who continually helped students reflect on what they were doing and define and evaluate their goals and strategies. He did not simply step back and let students flounder on their own. Papert's descriptions of LOGO teaching focused primarily on discovery learning. In contrast, Papert's actions as a teacher fit very well with constructivist models of curriculum, assessment, and instruction that advocate scaffolding and mediation by teachers and others rather than discovery learning (e.g., A. L. Brown & Campione, 1994; Lin et al., 1995; Vygotsky, 1978, 1986). As research with LOGO has focused more attention on the teaching that surrounds it, the results on cognitive transfer have been more favorable (e.g., Lehrer et al., 1994; Mayer, 1988a).

Applications (Tools). Technology in this category refers to software that supports various user activities such as writing (e.g., word-processing systems), calculating (e.g., spreadsheets), and the composition of multimedia documents as in the use of Hypercard (Apple systems), Linkway (MS-DOS systems), ToolBook (Windows systems), or Media Text (Hay et al., in press).

Means et al. (1993) note that many new hypermedia applications support the emergence of novel genre that exploit the capacities of hardware environments. The nonlinear format enables students to engage in different kinds of knowledge construction activities than would be possible with strictly linear applications. The products students create sometimes take advantage of the nonlinear capabilities, although sometimes they do not look much different than a typical report (e.g., Carver et al., 1992; Duffy & Knuth, 1990; Honebein et al., 1993; Lehrer, 1993; Spohr, 1994).

As noted earlier, computer applications tend to be treated differently when used in the context of constructivist models of education (cells 4, 5, and 6) compared with transmission models (cells 1, 2, and 3). In many classrooms based on transmission models, the applications are the curriculum. In constructivist-inspired classrooms, applications are usually treated as tools for reaching other goals, as in QUILL (Bruce & Rubin, 1993). These goals include solving important problems, building knowledge about new ideas and concepts, or creating text or multimedia documents about specific areas of research (e.g., Collins et al., 1991; Carver et al., 1992; CTVG, 1992a, 1994b; Lehrer, 1993; Scardamalia et al., 1994; Spehr, 1994).

A second way in which applications are affected by transmission versus constructivist models involves the degree to which they are augmented to provide support for learning. Early computer-based research on writing, conducted within the traditional school-based writing framework, asked whether writing on the computer was easier or better than writing by hand, and did not use the technology to augment the task environment. Results were equivocal regarding benefits, although it appeared that revising was more likely on the computer (e.g., Bradley, 1982; Datute, 1985b; Gerlach, 1987; Kerchner & Kistinger, 1984; MacArthur & Graham, 1987; Vecc, 1987; Woodruff & Bereiter, 1982). Despite the greater likelihood of revision, many of the revisions dealt with spelling, grammar, and punctuation. Meaning-based revisions such as reorganization, insertion, or deletion of information rarely occurred (Hine, Goldman, & Cossen, 1990).

QUILL is an early example of an augmented environment for writing. It was designed to provide opportunities for children to collaboratively solve problems and to have access to real audiences for their writing (Bruce & Rubin, 1993). The pedagogical goals for QUILL also included an emphasis on the integration of reading and writing, making writing public to establish community and meaningful communication with an audience, and revision. The computer environment consisted of four interrelated programs: Writer's Assistant, for word processing (Levin, Boruta, & Vasconcellos, 1983); Planner, for supporting brainstorming; Library, for sharing written work with other students; and Mailbox, an electronic mail system. The QUILL system was used during a yearlong implementation (1983–1984) in 20 classrooms in Alaska. Results indicated that students appropriated a number of meaningful goals for writing, most notably newspapers and mail. The system had little impact on revisions, however.

Examples of other environments for supporting writing are Salomon's Writing Partner (Salomon, 1993b), Rubin's Story Maker (Rubin, 1980, 1983); and the CTVG's work on reading support to help learning handicapped students develop their own multimedia designs (CTVG, 1994b).

Computer tools have also been developed to help teachers conduct the kinds of performance assessments that are consistent with constructivist curricula (e.g., Gearhart, Herman, Baker, & Novak, 1992; Hawkins et al., 1990; Lesgold, Eggen, et al., 1992; Shingold & Frederiksen, 1994). For example, electronic portfolios allow teachers easily to capture and store records of student progress that include text, audio, and video (e.g., the Grady Portfolio, developed by Aurbach & Associates,
Bar code readers have also been used by teachers to score performances and send these scores to a computer to be stored (e.g., Victoria Learning Society & Sunburst/Wings for Learning, 1994). Portable computers such as the TYCHO system (Stewart & Watson, 1994; Vecchione, 1994) and systems for the Newton (Victoria Learning Society & Sunburst/Wings for Learning, 1994) are being used for assessment as well.

Work under way as part of the Jasper series is examining the idea of having students learn to construct "SMART Tools" that enable them to solve classes of problems efficiently. For example, in the Jasper adventure Working Smart, the challenge is to construct a set of SMART Tools that allows students to qualify for an exciting job opportunity. Initial data indicate that students are motivated to construct SMART Tools and that the process of doing so helps them discover important mathematical patterns and concepts. The construction of SMART Tools also provides an excellent way to make students' thinking visible to themselves, their teachers, and their peers.

Overall, research indicates that an application's or tool's impact on the learner or educational setting depends on how it is implemented (e.g., Daiute, 1985a; Daiute & Kruidenier, 1985), and also on whether the technology leaves a "cognitive residue" (Salomon, 1993b; Salomon et al., 1991). Salomon and colleagues argue that the use of a cognitive tool ought to result in changed understandings on the part of learners. Such changes are effects of the technology, not just effects achieved with the technology. Effects of technology are ones that learners can transfer to new situations. Important research issues concern appropriate methodologies and benchmarks for examining performance in new situations.

Communication and Telecommunication. Implicit but central to constructivist-based applications is communication. Knowledge is constructed through conversations—whether face-to-face or electronic, whether synchronous or asynchronous, whether spoken or written (see Pea & Gomez, 1992). Technologies for supporting conversations are undergoing rapid change.

An exciting communication technology that supports collaboration is CSILE (Scardamalia et al., 1989, 1992). It is designed to provide opportunities for groups of individuals to collaboratively build new understandings and theories. Because all students on a network share an easily accessible data base, they can collaborate even though they cannot all be in the same place at the same time.

Additional examples of within-school systems that support collaborative learning are the Collaborative Learning Laboratory (Koschmann, Myers, Feltovich, & Barrows, 1994), which is used to facilitate collaboration among team members engaged in medical preclinical education, and EarthLab (Newman, Goldman, Brienne, Jackson, & Magzamen, 1989; S. V. Goldman & Newman, 1992), which provides support for coordinated investigations by small groups of students. (For further discussion of collaborative systems see the Journal of Learning Sciences, Vol. 3, No. 3, 1994, a special issue guest edited by Koschmann.)

Bubble dialogue (O'Neill & McMahon, 1992) is another promising tool that promotes conversation and collaboration. It is especially useful for helping students deal with complex emotional issues that they might otherwise have difficulty discussing. It does so by engaging students in computer-based role-playing scenarios structured to allow greater amounts of student reflection as they discuss complex aesthetic issues concerning literature and social themes (Kantor & McMahon, 1994).

The use of communications technology to encourage within-school collaborative knowledge building falls within cell 5 of the LTC framework (individual classrooms). The increased capabilities of networked electronic systems to support interactive information storage and exchange are giving rise to systems that support wide-area communal data bases that may be added to, accessed by, and operated on by communities of learners. With a sufficiently large bandwidth, wide-area systems can also support audio and video messaging in addition to text-based communication. Programs such as these fall within cell 6 (connected classrooms).

There are also numerous examples of wide-area communication systems that provide participants with the ability to share data bases asynchronously. One is the AT&T Learning Circle, in use by teachers (Riel, 1990a, 1990b, 1991b). LabNet is also a tool for teachers and students, particularly with regard to assessment (Ruopp, Gal, Drayton, & Pfister, 1993). Recently, Thought Box (Alexander & Lincoln, 1989), originally designed to support distance learning, has been redesigned to allow for more humanlike interfaces and collective construction of theme or topic-based group knowledge. CSILE (Scardamalia et al., 1994) is also being expanded to TeleCSILE in order to support wide-area communication. Project-based learning in science is supported by systems such as ALICE (Parker, 1991) and the CoVis Collaboratory Notebook (Edelson & O'Neill, 1994). Desktop videoconferencing has been used to support school-community interactions such as tutoring sessions on problem solving held between college students and students in middle schools (CTGV, 1994a).

An important characteristic of the communication technologies discussed above is that they are usually introduced as a means to solve complex problems or engage in collaborative inquiry around authentic problems. Additional well-known projects of this type are National Geographic Society (NGS) Kids Network (Jylwan, 1991; Technical Educational Research Center, 1990; Tinker & Papert, 1989), the Technical Educational Research Center's (TERC) Star Schools Project (Berger, 1989), the Jason Project (1993), AT&T's Long Distance Learning Network (Riel, 1991a, 1991b; Riel & Levin, 1990), the CoVis project (Pea, 1994), the Co-NCT Project (Bolt Beranek & Newman, 1994a; Richards, 1993) and the Intercultural Learning Network (J. A. Levin, Riel, Miyake, & Cohen, 1987). In a number of programs, electronic mail has also been used to provide students with access to subject matter experts (Campione, Brown, & Jay, 1992; Newman, 1990b).

There is so much activity over electronic mail that tools for organizing the profusion of messages are beginning to emerge (e.g., J. A. Levin & Jacobson, 1993). Similarly, the need for organizational tools emerges quickly in the context of the CSILE communal data base. Cohen (1994) has developed a set of electronic teacher tools that allow teachers to search data bases to find high-density topics of conversation as well as the individual contributions of particular individuals. Tools such as these are extremely helpful for monitoring group discussions and keeping them on track. Experiences of other projects involving
network-based classrooms in a wide variety of settings are reviewed in a recent volume by Bruce et al. (1993).

Issues arising in the context of electronic networks and communal data bases concern fundamental issues in knowledge organization, including search heuristics, psychologically adaptive schematics for supporting users' understanding of the data base landscape, and systematic but psychologically plausible updating mechanisms. When students are free to put in their thoughts and coconstruct knowledge, misconceptions often appear in the data base. What happens to such misconceptions is an important issue for research. As well, general questions about information sharing in electronic environments and communication etiquette (e.g., postulates for electronic conversations) are important for understanding the sociolinguistic implications of technology and the building of discourse communities. For a discussion of these issues see Mason and Kaye (1989) and Sproull and Kiesler (1991).

**Issues that Arise in Moving from Laboratories to Classrooms to Connected Classrooms.** The preceding discussion focused on the general implications of moving from the first row of the LTC framework (transmission models) to the second row (constructivist models that transform part of the school day). In this section we discuss some of the implications of moving across the second row, that is, moving from laboratories to classrooms to sets of connected classrooms.

Examples from Our Own Research. First, we reiterate that research in all cells of the LTC framework is valuable. For example, in our own work on the Jasper Woodbury Problem Solving Series, research conducted in laboratory settings (cell 4) has allowed us to compare the effects on transfer of having students work with Jasper versus having students work for the same amount of time with the same subproblems that are found in Jasper, but without the integrated problem context. By using teachers from our own research team in the context of laboratory studies, we were able to ensure a high degree of fidelity of implementation for both our experimental and control conditions. By focusing on a relatively small number of students, we were able to conduct in-depth assessments that asked students to think aloud as they attempted to solve new transfer problems (S. R. Goldman et al., 1991; S. R. Goldman & CTGV, 1991; Van Haneghan et al., 1992). These studies allowed us to document that opportunities to work in integrated problem contexts such as Jasper were very important (e.g. CTGV, 1993b; Van Haneghan et al., 1992).

In contrast to laboratory research, studies of Jasper that involved classrooms (cell 5) revealed a different set of problems and opportunities. The opportunities were that we were able to study the effects of Jasper as it was taught by a variety of classroom teachers in nine different states (CTGV, 1992d, in press; Pellegrino et al., 1991). However, large-scale studies also involve new problems. One was that we were unable to study the fidelity with which Jasper was implemented in each classroom. Another problem was that the best we could do for comparison groups was to find students with similar levels of achievement and economic status who received "regular classroom instruction" in mathematics rather than Jasper. A third problem was that we had to settle for paper-and-pencil assessment rather than in-depth performance assessments.

Overall, it was impossible to be as precise about the Jasper instruction, and the instruction received by comparison classes, as it was when we conducted our studies in laboratory contexts. Nevertheless, the opportunity to study Jasper across a large number of different sites was extremely beneficial (CTGV, 1992d, in press; Pellegrino, 1991).

We have also studied Jasper in the context of connected sets of classrooms (cell 6). The Jasper "SMART Challenge" Series was designed to connect groups of classrooms and teachers so that they could learn from one another (CTGV, 1994a). Data indicate that this increased the achievement of students relative to Jasper-alone instruction, and it also helped change teachers' teaching styles (e.g., B. Barron et al., 1995; CTGV 1994a).

Additional Examples of Migration. During the past 5 years, an increasing number of researchers have migrated from the laboratory to classrooms and sets of classrooms (e.g., Hawkins & Collins, in press; Mandinach & Cline, 1994; McGilly, 1994; Salomon, 1992). In the process, they have discovered issues with important implications for the design and use of technology. Collins (1996) provides an insightful discussion of some of the design tradeoffs that must be considered in schools.

An extremely important lesson from a number of different projects is that designers must focus simultaneously on issues of curriculum, instruction, assessment, and professional development. If any of these issues is ignored, applications often fall short of their designers' goals.

Means et al. (1993) provided an example of the need to consider assessments in her discussion of a California school system that implemented a constructivist-based technology program that changed the schools' curriculum, instruction, and professional development. However, the assessments were not changed, and they focused on specific skills rather than on more complex performances. Students did poorly on the skills tests, and the system began to question the technology. To be effective, assessment must be aligned with one's educational goals (see also S. R. Goldman et al., 1994).

The need to focus on instruction is illustrated by early efforts to implement LOGO. As noted previously, early implementations of LOGO tended to treat it as a new addition to the curriculum without paying serious attention to the nature of the instruction and formative assessment needed to support the goals of Papert and his colleagues (see Mayer, 1988a). In many classrooms, students were more likely to take a trial-and-error approach to LOGO programming than to approach the task as designers who plan and debug their own work (e.g., Littlefield et al., 1988). Later efforts to teach LOGO have been more successful at demonstrating cognitive benefits, in part because they (a) structured the instruction to encourage planning and reflection and (b) designed assessments that were more sensitive to the thinking processes that students developed (e.g., Lehrer et al., 1994).

Research conducted by Schofield et al. (1990) provides an excellent example of the effects of instructional context on learning. She studied Anderson and colleagues' geometry tutor in classroom contexts and found that a low degree of peer competition was a vital factor in promoting learning. These kinds of insight would be difficult to discover if one worked solely with individual students in the context of research laboratory.
A lesson learned by a number of research groups, ours included, is the need to pay a great deal of attention to the professional development of teachers who will be using the programs (e.g., Hawkins & Collins, in press; Mandinach & Cline, 1994; McGilly, 1994). Initially, many researchers underestimated the importance of this aspect of research, and their results were underwhelming. Several groups have developed technology-based applications that are very promising for strengthening the ability of both preservice and practicing teachers to implement programs in ways that are successful (e.g., Ball, 1994; L. C. Barron & Goldman, 1994; Duffy, in press; Fishman & Duffy, 1992; E. S. Goldman, Barron & Witherspoon, 1992; Kinzer, 1993; Kinzer et al., 1992; Lampert & Ball, 1990; J. A. Levin & Jacobson, 1993; J. A. Levin, Waugh, Brown, & Clift, 1993; Risko, 1992, 1993).

Summary of Row 2 of the LTC Framework

Changes in the goals of education and in views of human learning and human potential have suggested new visions of curriculum, instruction, and assessment. Technology can support these new visions, although it can support traditional ones as well.

Technology applications that fit within row 2 of the LTC framework (constructivist models of learning) look quite different from those that fit row 1 (applications based on transmission models). It has been challenging to move constructivist-based applications from laboratories (cell 4) into classrooms (cell 5) and connected sets of classrooms (cell 6) because most existing classrooms are based on transmission models of curriculum, instruction, and assessment. Technology researchers who have made the transition from cell 4 to cells 5 and 6 have discovered a number of new issues that did not arise in the laboratory. Issues of professional development—both for the technology and for new approaches to curriculum, instruction, and assessment—are challenging issues faced by virtually every research group we know.

THEORY AND RESEARCH RELEVANT TO ROW 3 IN THE LTC FRAMEWORK

Studies that fit into row 3 in the LTC framework (cells 7, 8, and 9) are based on the same constructivist principles as those relevant to row 2 (cells 4, 5, and 6). However, there is a difference in the degree of restructuring involved, and this raises new theoretical and practical issues. Studies relevant to row 2 in the framework involve efforts to transform only part of schooling. Further, most of them involve studies of only a single application, such as Quill, CSILE, Thinker Tools, Co Vis, Jasper, and so forth. In contrast, studies relevant to row 3 in the LTC framework (cells 7, 8, and 9) involve efforts to transform all of schooling. This usually involves the need to study the effects of a whole suite of technologies on the overall learning environment that they support.

Theoretical Issues Relevant to Transforming all of Schooling

An important issue that arises as one moves from the goal of transforming part of the school day (row 2) to transforming all of schooling (row 3) involves the need to provide a balanced curriculum. In row 3 (cells 7, 8, and 9) it is no longer sufficient to simply be the mathematics advocate or the science advocate or the literacy advocate. Each of these advocates usually wants more time for his or her particular subject, but there is only so much time in a day. Researchers who work in row 3 must acknowledge that students can gain expertise in one area of the curriculum at the expense of losing opportunities to learn about other areas. One approach to this dilemma is to create projects that integrate traditional curricula (e.g., Berger, 1994; Berlin, 1994; CTGV, 1994a; Dossey, 1994; Mandinach & Cline, 1994; Steen, 1994; Tinker, 1994).

The responsibility of thinking about the entire school day also raises issues of compatibility among different classroom cultures as children change classes, issues of restructuring class periods to create blocks of time necessary to pursue problem-based and project-based curricula, and issues of links to the home and community. A number of non-technology-based reform efforts have collected valuable information about issues such as these (e.g., Comer, 1988/1993; Hilliard, 1988; H. M. Levin, 1987/1993; Madden et al., 1991/1993). Responsibility for transforming all of schooling also requires a new concern with issues of accountability. When working with only a single technology program, it is often easy to finesse requirements for local accountability because of the experimental nature of one's work, and because students' levels of achievement can be measured in other subject areas that are not the focus of experimentation. Accountability issues must be directly addressed when one attempts to restructure the entire school day. Especially challenging are cases in which local tests of accountability are not consistent with the goals of the technology-based programs. Whether or not one believes in the value of these tests, they cannot be ignored (e.g., see example from Means et al., 1993, cited earlier).

We believe that the goal of transforming all of schooling, and of accepting responsibility for local accountability, is likely to encourage a careful examination of the use of "mixing models" of educational reform. For example, the more that we attempt to take responsibility for the student's whole day, the more we find ourselves inclined to combine constructivist-inspired activities such as problem- and project-based learning with more traditional drill-and-practice activities that fall into the laboratory setting row of the LTC framework (cells 1, 2, and 3) (e.g., Bransford et al., 1988; S. R. Goldman et al., 1988; Lin et al., 1995). However, we introduce these practice activities as part of a problem-solving curriculum in which students assess their own needs (e.g., to acquire particular skills) and work collaboratively to find ways to meet them. Under these conditions, there is great promise for well-structured diagnosis and practice software.

Research Relevant to Transforming all of Schooling

To our knowledge, there are only a few technology-based research projects relevant to row 3 in the LTC framework. There are, of course, a number of projects involving the restructuring of schools (see Backler & Eakin, 1993). However, most of them either (a) fall within cell 2 or 3 of the LTC framework (transmission models in classrooms and connected classrooms) or (b) make almost no use of technology.
One project relevant to row 3 (cells 8 and 9) is the Co-NECT project (e.g., Bolt, Beranek, & Newman, 1994a; Richards, 1993). Co-NECT schools are organized in multimedia clusters of approximately 100 students and four to five teachers. Each cluster is responsible for setting its own goals, planning curriculum, and monitoring progress. Technology is used extensively both within classrooms and schools and to connect different schools. Similarly, the STACI® project (Mandinach & Cline, 1994) connects teachers in schools across the country as they implement a systems thinking approach in multiple areas of the curriculum. Over the 8-year evolution of the STACI® (and its nonnetworked predecessor, STACI), teachers have formed dynamic, cross-disciplinary teams for the purpose of creating more meaningful, integrated curricula.

Another project relevant to row 3 (cells 8 and 9) is the Schools for Thought Project (e.g., Lamon, 1993; Lamon et al., in press; Lin et al., 1995). Named after John Bruer’s award-winning book, the project involves close collaboration among A. L. Brown and Campione’s (1994) “Fostering a Community of Learners” Project, Scardamalia and Bereiter’s CSILE Project (e.g., Scardamalia et al., 1994), the St. Louis Science Center and public schools, and CTGV’s Jasper Woodbury Project (e.g., CTGV, 1994a).

Initial work relevant to the Schools for Thought Project involved a restructuring of the entire school day in sixth-grade classrooms in several different cities. During the second year, the number of sixth-grade classrooms increased to four and the program expanded to four seventh-grade classrooms in order to create a corridor for the Year 1 sixth graders and connect different classrooms and schools through networking. The ultimate goal is to expand the program to both upper and lower grades.

The Co-NECT, STACI®, and Schools for Thought projects are relatively new and have not yet generated a great deal of hard data. What is clear, however, is that multiple methods are needed to understand and evaluate issues of student learning, program implementation, and professional development. Issues of performance assessment and accountability are high priorities for these research groups in the coming years.

## ISSUES FOR THE FUTURE

We believe that future research in technology and education will include work in all cells of the LTC framework, but especially in row 3 (cells 7, 8, and 9). Work in all cells is important because each offers unique strengths and opportunities. Work in row 3 is important because there is a strong need to study entire systems rather than look only at piecemeal effects (see Mandinach & Cline, 1994). Attempts to work in these cells raise a number of new issues that we believe will receive increasing attention. We discuss several of them below.

### Expanding the Scope of the LTC Framework

In our discussion so far, the scope of research within each cell in the LTC framework has been left undefined. For example, when we discussed constructivist approaches that attempt to transform all of schooling in connected classrooms (cell 9), we did not specify whether the scope of analysis was a single grade, middle school, kindergarten through Grade 12, or kindergarten through college. The scope of most research projects involves only a single grade level or, at most, two or three consecutive grade levels. There are important differences between thinking about changes within a single grade or small set of grades, and thinking about changes from kindergarten through college. These differences are illustrated in Figure 25–3.

A. L. Brown and Campione’s (1994) Community of Learners project is a good example of a project with a broad-scope focus. They emphasize the importance of “deep principles” in areas such as biology (deep principles might be “interdependence,” “biological diversity,” and so forth). Most important for the present discussion, Brown and Campione also explicitly attempt to create curricula and instructional opportunities that enable students to understand deep principles at early ages, and then to have the opportunity to expand their understandings as they progress throughout the grades. One advantage is that students can develop a level of expertise in particular domains that is extraordinary by current standards. Another advantage is that students can engage in cross-age tutoring sessions that include highly sophisticated discussions. To take this approach, one must be willing to rethink existing curricula, instruction, and assessment across multiple grades.

Kaput and Lesh (1994) have discussed the importance of a broad-scope focus in the area of mathematics. Why, they ask, should students suddenly be confronted with the course in algebra or geometry or calculus? Similar to Brown and Campione, they argue that there are “big ideas” in mathematics that can be introduced early and gradually refined over the years.

We believe that a broad-scope focus may be necessary for truly profound changes in academic achievement. In addition to helping students acquire more in-depth knowledge, it can provide new avenues to expertise that are denied to many students who are expected to learn an entire subject matter all at once when they receive the course in algebra, genetics, and so forth. Ideally, broad-scope approaches to education will attempt to integrate curricula from kindergarten through college so that mathematics, science, literature, and other subjects may be learned synergistically (Bransford, Sherwood, & Hasselbring, 1988). To achieve these ideals, technology-based applications must be designed with broad-scope goals in mind.

### Technology in the Service of Learning Communities

A concept that we believe will be increasingly important for the future thinking about technology is the concept of learning communities. We agree with Senge (1994) that the concepts of learning organizations and learning communities are in danger of becoming meaningless because they are being defined in almost every manner possible. Nevertheless, we think that these concepts are potentially very powerful ones that warrant rigorous research and theoretical articulation. We also believe that they are strongly linked to technology. Indeed, the STACI® project (Mandinach & Cline, 1994) has adapted these ideas in the analysis of teacher change in the process of learning to work in a technologically rich classroom environment. In the following discussion we discuss learning organizations and learning communities as they are being explored in both the business community and the education community.
Businesses as Learning Organizations. A number of insights into learning organizations and learning communities come from business leaders who need to cope with rapid change and reinvention and their implications for human capital (e.g., Knowles, 1983; Senge, 1990); our colleague Neal Nadler helped point us to the relevant literature. Traditional business structures have tended to be relatively inflexible and more likely to support the status quo than to support change. However, to respond to today's economic climate they must transform themselves into learning organizations (Mills & Friesen, 1992).

Mills and Friesen (1992) note that most organizations attempt to ensure learning by hiring good people. But one of the criticisms of current schooling is that it does not develop the kinds of flexible thinkers and problem solvers needed for modern-day organizations. Many businesses have begun their own training programs rather than rely on the schools. Unfortunately, business training programs often produce as much inert knowledge as traditional elementary, secondary, and college education. Authors such as Knowles (1983), Mills and Friesen (1992), and Senge (1990) provide important insights into the nature of the social and organizational structures that can overcome inert knowledge and help employees continue to learn, and to apply and refine what they know.

Mills and Friesen (1992) also emphasize that organizations must learn; otherwise nothing is preserved when people leave. Organizations learn by systematizing knowledge into practices, processes, and procedures, relying in part on what they can learn from their employees. We believe that theories of learning communities in elementary and secondary classrooms and preservice educational settings have much to learn from learning communities in business.

Classrooms as Learning Communities. Within the educational research community, much of the interest in learning communities stems from analyses of successful, informal learning environments that exist outside of school (e.g., Bransford & Heldmeyer, 1983; J. S. Brown et al., 1989; CTGV, 1993a; Lave, 1988; Lave & Wenger, 1991; Resnick, 1987b). For example, students who participate in successful informal learning environments typically do not spend most of their time simply memorizing what others teach them. In many settings (e.g., many apprenticeships), there is little formal teaching, yet a great deal of learning occurs (Holt, 1964; Lave & Wenger, 1991; Sternberg & Wagner, 1986).

In classrooms organized into learning communities, students are provided with opportunities to plan and organize their own research and problem solving, and to work collaboratively to achieve important goals (e.g., A. L. Brown & Campione, 1994; A. L. Brown et al., 1993, Carver et al., 1992; Collins et al. 1991; CTGV, 1994a; Lamon et al., in press; Linn & Burbules, 1993; Bolt, Beranek, & Newman, 1994a; Richards, 1993; Savery & Duffy, in press). In addition, learning communities usually emphasize the importance of distributed expertise (e.g., B. Barron et al., in press; A. L. Brown et al., 1993; Pea, 1993, 1994). Students are allowed to specialize in particular areas so that the community can capitalize on diversity. An emphasis on distributed expertise is distinctively different from environments where all students are asked to learn the same things at the same points in time.

Beyond Classrooms. The idea of classrooms as learning communities becomes most powerful when they, in turn, are seen as part of larger communities. The goal is to break the isolation
of individual classrooms and allow students, teachers, parents, and community members to interact. This is important for a number of reasons. One is that teachers and students can gain access to expertise that may not be available within the context of their classroom (e.g., B. Barron et al., 1995; A. L. Brown et al., 1993). Another is that opportunities to interact with others can provide important occasions for formative assessment by students and teachers (e.g., B. Barron, 1995, CTGV, 1994a).

Talbert and McLaughlin (1993) point out another reason for the importance of broader definitions of learning communities: Strong professional communities are essential conduits and learning contexts for ideas about new teaching practices. They note that these communities must exist in order to expect long-term change. In addition, they must consistently emphasize and support innovation and reform; otherwise they serve to reinforce the status quo and, in many cases, make teachers less rather than more flexible in adapting to student needs. A number of researchers are creating technology-based programs for building professional communities that look highly promising (e.g., Ball, 1994; L. C. Barron & Goldman, 1994; Duffy, in press; Everson & Smith, 1993; Jones, Knuth, & Duffy, 1993; Kinzer, 1993; Lampert & Ball, 1990; Risko, 1992/1993).

New Research Strategies

In keeping with an interest in learning communities, we believe that work in the future will evolve toward more collaborative research strategies. We do not argue that all research should proceed within the cell in the LTCT framework that attempts to transform all of school in connected sets of classrooms (cell 9). Research in every cell is important and has valuable insights to provide. For example, as discussed earlier, some issues that we have been able to study in laboratory contexts (cell 4) would have been practically impossible to study in classroom contexts (cells 5 and 6) (CTGV, 1993), and vice versa.

Collaborative Testbed Studies. A relatively recent strategy for evaluating technology programs is the idea of national testbeds (e.g., Bolt, Beranek, & Newman, 1994b; Hunter, 1993). Hunter (1993) notes that testbeds involve collaborative inquiry in networked communities over relatively long periods of time.

A new research strategy that we see emerging involves closely coupled links between research conducted in laboratory contexts (cells 1, 4, and 7) and testbed research that involves constructivist approaches to classrooms and connected classrooms (cells 5, 6, and 8, 9). The interplay between these two types of endeavors can be highly synergistic. As noted earlier, laboratory studies provide the kinds of controlled conditions that allow precise examination of variables. The downside is that many issues of real classrooms and learning communities never emerge in these kinds of settings. Work in classroom contexts (cells 5, 6, 8, and 9) provides opportunities to discover new, important issues that might eventually be capable of more precisely focused research. Note that this research strategy does not necessarily mean that one research group is responsible for everything. Different groups can take on different components of overall research projects. What is important is a tight coupling of projects so that research and practice are closely linked.

We also believe that efforts to transform all of schooling according to constructivist principles (cells 8 and 9) can breathe new life into the perceived importance of studies conducted in the first row of the LTCT framework (research based on transmission models). As noted earlier, the more one begins to take responsibility for the whole child, the more one realizes that part of children's learning is the opportunity to practice skills and develop some degree of fluency. When technology-based skill packages are introduced as part of a problem-solving environment where students define learning goals and attempt to accomplish them, we believe that they can do a lot of good.

Value-added Studies. A second research strategy we see emerging is related to the previous one but slightly different. It involves studies that assess the "value-added" of adding technology components to existing efforts at school reform. For example, many of the restructuring projects facilitated by the work of Slavin (Madden et al., 1991/1993), H. M. Levin (1987/1993), Comer (1988/1993), and others (see Backler & Eakin, 1993; Prestine & Bowen, 1993) are quite successful but make very little use of technology. Can the addition of well-motivated, technology-based curricula, tools, assessments, and performance supports for professional development increase the effectiveness of these environments? We believe that the answer is a definite yes. But to our knowledge, such research has not yet been attempted.

New Roles for Researchers, Developers, Teachers, and Students

We believe that efforts to restructure schools will require new roles for researchers, developers, teachers and students. Usually, researchers and developers study interventions that they develop or which they are particularly knowledgeable about. However, it is unlikely that any researcher or research group can create products necessary to meet the goal of transforming all of schooling. This means that different groups must collaborate. In order to do so, they must give up the role of always being the experts who teach others; they must also adopt the role of novices who attempt to learn about their colleagues' programs.

In implementing the Schools for Thought project (Lamon et al., in press; Lin et al., 1995), the challenge of collaborating with other research groups has been extremely revealing to us. For example, we were very familiar with A. L. Brown and Campione's work (1994) and Scardamalia and Bereiter's work (Scardamalia et al., 1994). However this familiarity was at the level of talking about the programs from a theoretical perspective and discussing their results. We discovered a large gap between this level of knowing and the knowing required to actually implement these ideas in classrooms. It became clear that a several-day or even several-week workshop was insufficient. We needed (and still need) opportunities for frequent interactions with experts in each program as the implementation progresses in the classrooms. Teachers need similar kinds of support.

Constructivist-oriented classrooms also require new roles for teachers and students. Teachers must be able to accept the role of learner rather than always be the expert. Students must learn to work collaboratively rather than always compete.

We are optimistic about the increasing need for different
groups to collaborate. It forces the research community to learn how difficult it can be to understand others’ ideas at a level necessary to implement those ideas. As researchers learn to appreciate the challenges faced by novice learners, they should be able to collaborate better with teachers, parents, principals, and other community leaders who, collectively, are necessary for the development of successful learning communities.

**New Appreciation of Realities**

Increasing efforts to restructure all of schooling (cells 8 and 9) should also help the research community appreciate some realities of educational reform that become especially salient when one attempts to “scale up” programs and study them on a broad scale.

**Equity.** There is a great deal of concern about equity and technology, in part because equity has such a powerful impact on the life chances of individuals (e.g., Backler & Eakin, 1993; Boruta et al., 1983; Hawkins, 1987a, 1991; Hawkins & Sheingold, 1985; Hollins, King, & Hayman, 1994; Lepper & Gurtner, 1989; Malcolm, 1991; Prestine & Bowen, 1993; Ramirez & Bell, 1994a; Sabell & Barrett, 1994; Sutton 1991; Warren & Rosebery, 1993). Federal agencies are looking at equity issues from the perspective of a National Information Infrastructure through Internet and other resources (e.g., Clinton & Gore, 1993; National Information Infrastructure, 1994).

The research community can play an important role in achieving equity by demonstrating the value of adding technology to existing educational programs—especially programs for traditionally underserved populations (e.g., Bransford et al., in press). As the added value becomes clear, there should be more pressure for state and federal agencies to provide the technologies necessary for success for all. The research community also needs to help policy makers and others understand that support for helping teachers learn to use technology is extremely important. This brings up lessons of infrastructure.

**Infrastructure.** An interesting session at the 1994 Association for Educational Computing Technology conference was called “Building Planes That Fly.” Participants discussed questions such as how engineering principles and theories of physics were combined by the Wright brothers, and how similar approaches might be used to develop technologies that fly. Discussions in the session were fruitful and went in a number of directions. However, one participant noted that the problem of education goes far beyond the challenge of building a single airplane. Instead, it is more analogous to the challenge of creating and maintaining an air transportation system for a nation. To achieve the latter, one needs a vast infrastructure that includes plane manufacturers, airplane mechanics, fueling services, ticketing services, meal services, airports, vehicles and roads to get to and from the airports, places for people to stay once they reach their destinations, continual training programs for pilots and mechanics, and so forth.

The importance of infrastructure is often forgotten when we think about new technologies such as computers for the schools. We tend to dump them into classrooms in a manner analogous to giving a small, isolated town an airplane without also giving it a pilot, mechanic, fuel service, or runway. One of the important lessons learned by those who have moved from laboratories to schools is that the technology infrastructure in school buildings is virtually nonexistent. In some cases, projects have had to assume responsibility for phone line installation, electrical work, appropriate furniture, and so forth, as well as supply computer hardware and software (see CTGV, in press, and other chapters in Hawkins & Collins, in press). The infrastructure for school personnel to develop the knowledge necessary to function in constructivist and technology-rich environments is a primary concern and one that has begun receiving attention at federal, state, and local levels in both the public and the private sector. The necessity for infrastructures for technology in education needs to be recognized, and funded, so that technology has a chance to contribute to the kind of revolution in learning that many envision.

**SUMMARY**

Our goal in this chapter has been to provide a framework for thinking about research on technology and education. We noted the impossibility of attempting an exhaustive review of all relevant research because the area is too massive. At a minimum, an exploration of the potential benefits of technology for education requires a discussion of the three areas illustrated in Figure 25–1—technology, learning theory, and educational issues. Therefore, our goal was to provide an overview of where research has focused in the past and where it might go.

Our discussion of past and future trends in research was organized around the LTC framework that was introduced in the first section and illustrated in Figure 25–2. We call it the LTC framework because it focuses on looking at technology in context, where context includes the theoretical context for the application (transmission theories vs. constructivist theories) as well as the educational context in which the application is used (e.g., laboratory, classrooms, connected classrooms).

In the second section we discussed research relevant to row 1 of the LTC framework, which involved early research on technology and education. This work took existing classroom practice as a given, and typical practice was usually consistent with a transmission model of curriculum, instruction, and assessment. Because they could be assimilated into existing practice, the technology applications studied by early researchers could move relatively easily from laboratories to classrooms and connected classrooms.

In the third section we focused on row 2 of the LTC framework and noted that research conducted during the past several decades suggests that transmission models of instruction are no longer sufficient because of changes in educational goals in response to new societal needs for lifelong learning. We discussed new visions of human learning and human potential and related them to changes in assumptions about curriculum, instruction, and assessment. These changes reflect a constructivist philosophy of learning rather than a transmission—reception philosophy. Technology developed from a constructivist perspective cannot simply be assimilated into traditional classroom contexts. Therefore, important issues arise as one attempts to migrate from laboratory to classroom contexts. Of particular importance is the fact that professional development involves
not only learning about technology, but learning about new philosophies of education as well.

In the fourth section we considered theory and research relevant to the third row (cells 7, 8, and 9) of the LTC framework. Theory and research in this row are also based on constructivist assumptions, but new issues arise when the goal becomes that of restructuring all of schooling rather than restructuring only part of a school day. We know of only a few technology-based research programs that fit into row 3 (cells 7, 8, and 9).

In the fifth section we looked at issues for the future. We noted that the LTC framework can be viewed three dimensionally, where the scope of the analysis (a single grade, a set of grades, kindergarten through grade 12 represents an additional dimension. Serious consideration of broad-scope issues (such as those encompassing all elementary and secondary schoolrooms) seems important because they have the potential to produce considerable change. We also argued that an important theoretical goal is to encourage further theory and research on the concept of learning communities and roles for technology in fostering and maintaining these communications. To do so requires new kinds of research designs, methodologies, and collaborations.

We ended by noting that research on educational technology needs to contribute to an increased appreciation of important realities such as issues of equity and the need to build an infrastructure that can enable technology to live up to its promise of encouraging extraordinary student achievement. Pursuing that promise on a broad scale is a major challenge for the next 10 years of research. It requires expansions of the issues on the educational psychology plate. Those expansions need to occur at the theoretical, methodological, and pragmatic levels and should apply simultaneously to technology, theories of human learning and potential, and educational practice.

References


national Conference on Distance Learning (pp. 2–11). Washington, DC: Brigham Young University—Hawaii Campus.


Progress in cognitive development research (pp. 171–190). New York: Springer.


mental models determine analogical transfer across problems with a common goal structure. *Cognitive Development*, 1, 103–121.


Jason project. (1993).


Risko, V. J. (1993). *What do teachers/administrators learn from video cases? Research working group at a working conference on Case-based Teaching, University of Nevada, Las Vegas*.


