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ABSTRACT

This literature review lays the groundwork for exploring potential linkages between constructivist learning theory and applications of technology. The first section provides an overview of constructivist learning theory, including the major concepts of constructivism, support for constructivist precepts, and confusions and controversies. Constructivism's implications for K-12 classrooms are identified in the next section, including the following elements of constructivist theory and their application in the classroom: the importance of prior understandings; learning as an adaptive activity; knowledge as constructed; resistance to change; learning as situated; and the role of social interaction. The third section describes the role of technology in constructivist learning environments; three major categories of instructional use for computer-based technologies are summarized--learning from technology, technology as the object of instruction, and learning with technology. The challenges of establishing constructivist learning environments and using technology to support them are addressed in the fourth section, including barriers to technology implementation, teachers' resistance to change, students' resistance to change, the dilemma of "right" answers versus student understandings, and the need for in-depth understandings of pedagogy, subject matter, and skills in using technology. A final section offers conclusions about creating constructivist learning environments supported by technology. (Contains 141 references.) (AEF)

Constructing Knowledge with Technology

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Introduction

This report is grounded in the idea that "theories of learning and prescriptions for practice must go hand in hand" (Duffy & Jonassen, 1992, p. 2). Both separately and in tandem, constructivism — a learning theory — and technology — an aid to instructional practice — are receiving increasing attention in current efforts at educational reform. However, the elements of constructivist theory, their implications for classroom practice, and the potential for technology to support instruction that is grounded in constructivist principles, often are addressed only in general and superficial ways.

Although constructivism is prominent in discussions of instructional improvement, the tenets of constructivist learning theory do not necessarily reflect the mainstream of belief among educational practitioners. Schifter (1996) describes the "beliefs about learning that still order most of our classrooms":

> that people acquire concepts by receiving information from other people who know more; that, if students listen to what their teachers say, they will learn what their teachers know; and that the presence of other students is incidental to learning. (p. 494)

There is a real danger that teachers are making only superficial changes while believing that they are implementing constructivist teaching approaches. As Taylor, Fraser, and Fisher (in press) report, "Our research has shown how readily traditional teacher-centered classroom environments can assimilate th[e] constructivist perspective and remain largely unchanged" (p. 3).

In a similar vein, technology — particularly in the form of computers and online networks — is proliferating in schools. According to surveys by Market Data Retrieval (1997), the number of computers in public schools grew by nearly two hundred percent over the period from 1991-92 to 1995-96. The National Center for Education Statistics (1998) reports that 78 percent of U.S. public schools had access to the Internet in 1997, up from only 35 percent in 1994. Yet the potential of these technologies to support new, more student-centered instructional approaches, remains largely untapped (Means and Olson, 1997; U.S. Congress, 1995).

This literature review lays the groundwork for exploring potential linkages between constructivist learning theory and applications of technology. The paper first outlines basic tenets common to most discussions of constructivism, then identifies, from the current literature, implications of these tenets for strengthening instruction in K-12 classrooms. A third section describes the use of technology to support instructional improvement based on the implication of constructivism. A final section outlines some of the challenges involved in using technology to support constructivist-oriented approaches.

An overview of constructivist learning theory

Constructivist theory has its roots in a number of disciplines, including philosophy, anthropology, the natural sciences, semiotics, socio-linguistics, and education. Its lineage has been variously described (see, for example, Duffy & Cunningham, 1996; and Entwistle, Entwistle, & Tait, 1991). In the field of education, both Rousseau and Dewey are often cited as incorporating constructivist perspectives into their views of teaching and learning. More recently, the focus on constructivism has emerged from the push for reforms in specific content areas, with science and mathematics education at the forefront (Brooks & Brooks, 1993).

In education, constructivism is often discussed as a philosophy or instructional approach. As Catherine Fosnot observes, however, "Constructivism is not a theory about teaching. It's a theory about knowledge and learning" (Brooks & Brooks, 1993, p. vii). The confusion of the two has led both to controversy and to a tendency to consider constructivism as merely one in a broad array of concepts on which teachers can draw in seeking to improve student learning. For any learning theory to be of use, it is certainly necessary to identify and explore its implications for teaching. But it is critically important to consider constructivism first purely through the lens of learning theory, i.e., *what is* (according to the constructivist perspective), rather than *what should be.*

Major concepts of constructivist learning theory

Duffy and Cunningham (1996) point out that "the term *constructivism* has come to serve as an umbrella term for a wide diversity of views" (p. 171). Some authors distinguish between *cognitive constructivism,* which focuses on the individual learner, and *social constructivism,* which emphasizes learning as occurring within the context of dialogue and social interaction (Duffy & Cunningham, 1996).

Definitions of constructivism under any of these views, however, include as central the idea that knowledge is "constructed" by the learner. For example, Honebein, Duffy, and Fishman (1991) state, "Basically, constructivism proposes that knowledge or meaning is not fixed . . . but rather is constructed by individuals through their experience . . . in a particular context" (p. 88). Embedded in this statement are a number of concepts that run counter to the beliefs still shaping instruction in U.S. schools today: that learning is adaptive, a process of building functional understandings rather than of uncovering fixed truths; that learning is an active process controlled by the learner; and that learning and the context for learning are deeply intertwined (Brooks & Brooks, 1993; Duit, 1995; Duffy & Cunningham, 1996). There are other important concepts as well, particularly the role of social interaction in both mediating and facilitating the learning process.

Learning as an adaptive activity. Constructivist theory characterizes learning as sense-making. Brooks and Brooks (1993), for example, state, "Each of us makes sense of our world by synthesizing new experiences into what we have previously come to understand" (p. 4). Learning is a process of developing ever-more-powerful understandings; the activity is not one of acquiring a fixed body of knowledge, but of building concepts and explanations that allow us to function effectively in a given context and that adequately account for the circumstances presented to us:

> Taken as the advancement of *understanding*, the cognitive endeavor starts from what happens to be currently adopted and proceeds to integrate and organize, weed out and supplement, not in order to arrive at truth about something already made but in order to make something right — to construct something that works cognitively, that fits together and handles new cases, that may implement further inquiry and invention. (Bauersfeld, 1995, p. 144, quoting Goodman & Elgin, 1988)

Knowledge, in this view, is not fixed; it is not possible, in fact, to determine objective truth with any absolute certainty. Duffy and Cunningham (1996) state that "what we choose to call *knowledge* is a consensus of beliefs, a consensus open to continual negotiation" (p. 178). Rather than the approximation of objective reality, then, "viability" is the appropriate measure of understanding. As von Glasersfeld (1995a) observes, "To the biologist, a living organism is viable as long as it manages to survive in its environment. To the constructivist, concepts, models, theories, and so on are viable if they prove adequate in the contexts in which they were created" (pp. 7-8).

Learning as situated. The quotation by von Glasersfeld focuses on understandings within "the contexts in which they were created." Constructivist theory describes knowledge as inextricably tied to the circumstances in which it is constructed and used:

> Recent investigations of learning . . . challenge [the] separati[on] of what is learned from how it is learned and used. The activity in which knowledge is developed and deployed, it is now argued, is not separable from or ancillary to learning and cognition. Nor is it neutral. Rather, it is an integral part of what is learned . . . Learning and cognition, it is now possible to argue, are fundamentally situated. (Brown, Collins, & Duguid, 1989, p. 32)

If knowledge is defined as understandings that can be put to use, as was suggested in the preceding section, then knowledge may be characterized as "similar to a set of tools," and, like tools, "can only be fully understood through use":

> It is quite possible to acquire a tool but to be unable to use it. Similarly, it is common for students to acquire algorithms, routines, and decontextualized definitions that they cannot use and that, therefore, lie inert . . . People who use tools actively rather than just acquire them, by contrast, build an increasingly rich implicit understanding of

> the world in which they use the tools and of the tools themselves. (Brown, Collins, & Duguid, 1989, p. 32)

Knowledge, according to this view, is never completely abstract or independent from its context. *Context* may include the learner's reasons for seeking new understandings as well as the nature of the learning problem, its complexity, and the physical and social circumstances in which it is embedded (Honebein, Duffy, & Fishman, 1991).

Traditional schooling simplifies knowledge and practice, presenting concepts and information abstractly rather than in a context of meaningful application (Resnick, 1989). When students memorize formulae, definitions, and the like, divorced from applications that have meaning to them, then the context for learning becomes merely that of passing a test or getting by in the classroom, and students' capacity to retain and apply the content is limited (Duit, 1991).

Knowledge as constructed by the learner. Learning as sense-making is an active process; the learner is an actor, not a passive recipient of information. As Perkins (1992) describes it, "Learners do not just take in and store up given information. They make tentative interpretations of experience and go on to elaborate and test those interpretations" (p. 49). Constructing knowledge, moreover, is not merely a mechanical process of sorting and processing as a computer might. Duffy and Cunningham (1996), analyzing the metaphors used to characterize learning, contrast the mechanistic image of "mind as computer" with their conception of "mind as rhizome":

> The metaphor of rhizome specifically rejects the inevitability of such notions as hierarchy, order, node, kernel, or structure. The tangle of roots and tubers characteristic of rhizomes is meant to suggest a form of mind where . . . there are no fixed points or positions, only connections (relationships) . . . the structure is dynamic, constantly changing . . . Learning, then, is neither a matter of discriminating the symbols of the world and the rules for manipulating them nor of activating the right connections in the brain. It is, rather, a matter of constructing and navigating a local, situated path through a rhizomous labyrinth. (p. 177)

In building ideas, then, learners draw on a complex web of experiences, voices, sensory input, and other information. As Brooks and Brooks (1993) put it, "Our perceptions and rules are constantly engaged in a grand dance that shapes our understandings" (p. 4). They use as an example a young girl who enters the ocean for the first time. She has experienced immersion in water only in bathtubs and swimming pools and so thinks of it "as calm, moving only in response to the moves she makes" (p. 4), and she has a certain conception of its taste. Her experience of the briny, tumultuous ocean water challenges these conceptions; from her old and new experiences and perceptions, the child must make new sense of the characteristics of water. In doing so, she does not merely add new information to the mental category of water, but changes her basic framework for thinking about it. In this case, Brooks and Brooks state, "learning is not discovering more, but interpreting through a different scheme or structure" (p. 5, quoting Fosnot, in press).

The role of experience and prior understandings. As the preceding example illustrates, the process of building new understandings is rooted in what we previously have experienced and understood. New experiences are internally mediated — compared, filtered, assessed — via prior experiences and understandings in an effort to find consistency. Von Glasersfeld (1995b) explains that, from our earliest sensory experiences, the human organism attempts "to establish regularities in its experience":

> The reason, on the simplest level, is that an organism that acts as if things that happen are likely to happen again can at least try to avoid situations it *does not* like (because they hamper or hurt) and to make those situations recur that it *does* like. As philosopher David Hume stated in the eighteenth century, if we do not believe that the world we live in repeats itself, we cannot draw inferences of any kind. (p. 369)

Sense-making begins with inferences built and tested through direct sensory experience. As we grow older, "experience" becomes more broadly defined, encompassing not only physical phenomena and action but conversation, observation, reading, and thought (DeVries & Kohlberg, 1990). Whatever the nature of the experience, an opportunity for *learning* takes place when we encounter something that appears inconsistent with our existing understandings:

> Often, we encounter an object, an idea, a relationship, or a phenomenon that doesn't quite make sense to us. When confronted with such initially discrepant data or perceptions, we either interpret what we see to conform to our present set of rules for explaining and ordering our world, or we generate a new set of rules that better accounts for what we perceive to be occurring. Either way, our perceptions and rules are constantly engaged in a grand dance that shapes our understandings. (Brooks & Brooks, 1993, p. 4)

A learner's encounter with objects or circumstances that do not fit her or his previous understandings and experiences, has been variously described as "disequilibration," or "perturbation," or, more simply, puzzlement (Duffy & Cunningham, 1996, p. 175). The learner seeks balance, or equilibrium; as Yager (1991) explains, this equilibrium

> is not static like a balance beam, but dynamic like that maintained by a cyclist. The brain is continually seeking to impose order on incoming stimuli and to generate models that lead to adaptive behavior and useful predictions. (p. 54)

Resistance to change. Duit (1995), among others, notes that "conceptions stemming from everyday experiences are usually deeply rooted. This is especially true of conceptions based on sense experiences" (p. 275). Having found a "balance" of understanding that appears to work in the circumstances encountered so far — and that may be further reinforced over time — the learner feels no need to examine, much less doubt, that understanding.

The more one's understandings recede from conscious awareness, the more difficult they become to change. Osterman and Kottkamp (1993) note a difference between "espoused theories," which they define as "what we are able to say we think and believe," and "theories-in-use," which are beliefs and assumptions existing, for the most part, beyond our conscious awareness and which exert much greater power over our actions and perceptions: "While espoused theories readily incorporate new information, theories-in-use resist change . . . While we [superficially] adopt new ideas, our behavior often continues unchanged" (p. 12).

When discrepancies do arise, a learner's first response generally is to seek explanations that do not require a shift in well-established understandings, and if the discrepancies seem irrelevant, they are simply ignored. As Shapiro (1994) points out, "In order to take on a new viewpoint, one must decide to let go of an old one. There must be a reason to decide to make a shift in thinking" (p. 7). Or, as Wheatley (1991) puts it, "Our path is viable as long as we do not run into a wall" (p. 11). Even when seemingly impassable "walls" appear, the human organism demonstrates a remarkable capacity for getting around or through apparent contradictions, by blaming some intervening factor, even by disbelieving one's own eyes (Duit, 1991).

The role of social interaction. One of the major areas of divergence among constructivists relates to their perspectives about the role of social interaction in the learning process (Duffy & Cunningham, 1996). Williams (1989; see also Newman, Griffin, & Cole, 1989) discusses the difference between cognitive constructivism, which emphasizes individual problem-solving and construction of ideas, and social constructivism, which posits that social interaction is not merely supportive of, but is an essential ingredient in, cognitive development. Social constructivism builds on the work of L. S. Vygotsky:

> Where cognitive theories move to the interior of the mind (what was going on to mediate stimulus and response), Vygotskian theory moves to the context of behavior, to the social situation within which the action takes place. . . In this view, cognitive abilities and capacities themselves are formed and constituted in part by social phenomena. (p. 109)

Whichever the emphasis, however, constructivists agree that social interaction is an important component in the learning process. As Duffy and Cunningham (1996) explain, thinking "is always dialogic, connected to another, either directly as in some communicative action or indirectly via some form of semiotic mediation: signs and/or tools appropriated from the socio-cultural context" (p. 177). Moreover, dialogue serves several functions, helping the learner to test and refine her or his ideas, introducing multiple perspectives, and negotiating limits on idiosyncratic conceptions:

> The constraints on constructed knowledge come largely from the community of which one is a member. . . By continually negotiating the meaning of observations, data, hypotheses, and so forth, groups of individuals construct systems that are largely consistent with one another. (Cognition and Technology Group, 1992, p. 117)

Support for constructivist precepts

It is not possible to definitively "prove" a learning theory, only to disprove it. However, a number of empirical studies support the power of constructivist theory in explaining the learning process. Studies of children's behavior in language acquisition and literacy (DeVries & Kohlberg, 1990; Seliger, 1991), mathematics (Aichele & Coxford, 1994; Bauersfeld, 1995; Schifter, 1996), and science (Driver, 1995; Duit, 1995; Shapiro, 1994; Wheatley, 1991), among others, indicate that prior to and independent of formal schooling, children seek regularities or patterns, and use them to build personal understanding of natural phenomena, language, symbols, and tools (DeVries & Kohlberg, 1990).

Studies reveal learners' — including adult learners' — resistance to changing their existing conceptions, even to the point of perceiving events differently than they actually occur. As an example, learners who believe an object's weight will influence the speed with which it falls to the ground, tend to report "seeing" a heavier object touch down before a lighter one, even though the two objects fall at the same rate of speed (Duit, 1991, 1995).

Studies also support the idea that social interaction plays an important role in supporting learning, although it remains difficult to characterize the precise role of social interaction (Driver, 1995; Duffy & Cunningham, 1996). For example, Driver (1995) reports on a study of the influence of group discussion on students' understanding of science concepts. Results

> indicate that all children make progress in their scientific understanding. . ., and that this progress occurs regardless of whether the group discussion reflects progress. This suggests that the progress in understanding is brought about not so much through the scaffolding offered by other children's ideas as the opportunity for each individual to reorganize his or her own ideas through talk and listening. (pp. 394-395)

Confusions and controversies

As is true for any system of belief, constructivism has generated disagreement and controversy. In education, the strongest protests generally focus on two related issues: one, whether constructivism is a comprehensive theory, accounting for all learning, or whether it explains only one of several types of learning; and two, whether it is possible to "know," and appropriate to teach, objective reality or truths, or whether all understandings are necessarily idiosyncratic (Brooks & Brooks, 1993; Duffy & Cunningham, 1996). In at least some instances, disagreements seem to be based on a confusion between constructivist learning theory and prescriptions for practice.

Is constructivism a comprehensive learning theory? Some authors argue that constructivism does not account for all learning. Merrill (1992), for example, attempts to distinguish between what he calls "extreme" and "moderate" constructivism. He states that "an extreme constructivist position. . . may be appropriate for some," but not all, "types of learning" (p. 107). Similarly, Stanovich (1994) distinguishes between elements of reading that are linked to reasoning processes and elements that are not, such as word recognition, and characterizes the latter as "anti-constructivist" (p. 260).

Others argue that "learners are always making meaning, no matter what level of understanding they are on," or what they are learning: "Constructivism is not a theory to explain only complex, ill-structured domains, it is a theory of how learners make meaning, period!" (Fosnot, 1992, p. 172; see also Lewin, 1995).

According to constructivist theory, learning is always active, and always involves sense-making. Perkins (1992) states:

> Even when the learning process appears to be relatively straight-forward, say a matter of learning a new friend's name or a term in a foreign language, constructive processes operate: Candidate mental structures are formed, elaborated, and tested, until a satisfactory structure emerges. (p. 49)

From the constructivist perspective, then, even memorization — which appears to many of us to be merely mimetic, a passive absorption of data — takes place within a framework of constructive cognitive activity. Such activity includes decisions as to what the learner commits to memory, the match between the original material and the way the learner perceives it, the purposes and duration for which the learner retains the information, the ways the learner does or does not apply the information, and the links to other knowledge that are made or not made (Brooks & Brooks, 1993; Perkins, 1992).

In a similar vein, some authors wonder, if learning is based on experience, how it is possible to learn from an activity such as reading. Honebein, Duffy, and Fishman (1991) explain:

> The learners (or readers) bring their own framework to the task. They have real. . . problems that they are trying to solve and they read the text with those problems in mind. Hence the reader is cognitively problem solving in the area of application (the authentic context) while reading the text. What information is attended to, how the information is organized, and what personal knowledge is combined with the information all revolves around. . . those contexts of application the reader imposes. (p. 93)

Objective vs. subjective viewpoints. Another area of frequent controversy relates to the extent to which it is possible to "know" objective vs. subjective truth. Bereiter (1994) discusses the objections raised by some authors to the assertion that, as he puts it, "there is no objective standpoint":

> This statement is sometimes taken simplistically to mean that there are no absolute truths, but that misses the point. The point is that there is no objective standpoint from which to judge whether something is an absolute truth. Also, the statement does not mean that there is no real, material world. It only means that we can never get down to an objective knowledge of it that can serve as a basis for our judgments, beliefs, and interpretations. (p. 4)

Merrill (1992), in opposing "extreme constructivism," describes extremists as arguing "that meaning is always constructed by, and unique to, the individual; that all understanding is negotiated" (p. 107). He believes, in contrast, that "a significant amount of what every child must learn — and certainly what any adult must learn to earn a living and function — is objective" (p. 112). He asks, "Do we want students to have a 'self-chosen position' with regard to the sound of letters in learning to read? Do we want students to have a 'self-chosen position' about the meaning of integers?" (p. 107).

The point constructivists make in response is that, whether we want them to or not, learners *always* have a subjective and "self-chosen position." However, as Duit (1995) notes, "Constructivism explicitly rejects the idea of solipsism." Rather, social interactions work to "prevent constructions of solely idiosyncratic conceptions" (p. 274). Whereas Merrill equates the "standard" view and the "objective" view, constructivists consider the "standard" view to be negotiated and subjective. The standard view may be the best, i.e., most viable available, but that does not make it objective.

Nor do constructivists argue that there is no place in the learning process for the standard view. Newman, Griffin, and Cole (1989), for example, note that

> children cannot and need not reinvent the artifacts that have taken millennia to evolve in order to appropriate such objects into their own system of activity. The child has only to come to an understanding that is adequate for using the culturally elaborated object in the novel life circumstances he [sic] encounters. (p. 63)

Confusing theory and philosophy. At least some of the debate over constructivist principles has resulted from the tendency to confuse learning theory with prescriptions or philosophies about how learning can best be supported. Both Stanovich (1994) and Merrill (1992), in their critiques of constructivist perspectives, make this error. Merrill, for example, in listing what he describes as "the assumptions of extreme constructivism," jumbles indiscriminately ideas about teaching and ideas about learning:

> that content cannot be pre-specified because every learning task is unique; that learners learn in idiosyncratic ways; that objectives or learning outcomes are content specific; that there are no categories of objectives; that there is no domain-independent instructional strategy; that there can be no external control of the instructional events except that which the learner chooses; that there are no isolated tasks, only real-world tasks; that there can be no simplification of content; that content cannot be separated from use; that the teacher must model the process but must not be scripted; and that there must always be alternative views. (pp. 112-113)

Such confusion, however, is not limited to critics of constructivism. Its advocates also sometimes jumble discussions of instructional approaches and descriptions of the learning process (see, for example, Simons, 1992). One result of this confusion is the perpetuation of the idea that it is possible for constructivism to become merely one more option in a teacher's instructional repertoire, undercutting the conclusion voiced by Bednar, Cunningham, Duffy, & Perry (1992), that "it appears that the implications of constructivism for instructional design are revolutionary rather than evolutionary. Viewed from contrasting epistemologies, the findings of constructivism replace rather than add to our current understanding of learning" (p. 30).

Constructivism's implications for K-12 classrooms

As Gergen (1995) notes, our beliefs about the nature of knowledge and about the learning process "inform, justify, and sustain our practices of education" (p. 17). How, then, do we move from constructivist learning theory to constructivist approaches to instruction? There are hazards inherent in attempting to extract ideas about teaching. Bednar et al. (1992) discuss the fact that "abstracting concepts and strategies from the theoretical position that spawned them strips them of their meaning" (p. 19). As the preceding section suggests, it is also easy to confuse theory and prescription in ways that diminish the power of both. On the other hand, where is the usefulness of theory without application? What seems most important is to be mindful of the difference between theory and application, in this case, between a focus on how people *do* learn (from the constructivist perspective) and how and what educators *want* students to learn and teachers to teach.

Related to this issue is a concern about nomenclature. The educational literature includes the terms "constructivist schools" (e.g., Brooks & Brooks, 1993), "constructivist classrooms" (Brooks & Brooks, 1993), "constructivist instructional design" (Knuth & Cunningham, 1991), "constructivist teaching" (Ackerman, 1995), "constructivist learning environments" (Duffy & Cunningham, 1996; Hannafin, Hannafin, Land, & Oliver, 1997), and other labels in reference to instruction that draws on constructivist principles. All of these terms present problems in that they can be interpreted to suggest that constructivism is merely one in a range of options for student learning. In this review, we refer primarily to "constructivist learning environments." From the perspective of constructivist learning theory, of course, *all* learning environments are constructivist, whether intentionally or otherwise (Fosnot, 1992). However, the focus from an instructional point of view is on *intentionality*, on consciously creating environments that capitalize on the way people learn.

As Lewin (1995) puts it, "the question is not whether knowledge is constructed (because by definition it must be), but whether the construction enables or distorts" (pp. 431-432). Constructivist learning environments, as the term is used here, are those in which instruction is organized to "enable," or facilitate, the learning of specified concepts and skills. In spite of its problems, the term seems preferable to "constructivist teaching" because of its emphasis on structuring a facilitative environment and its de-emphasis of "teaching" as it is traditionally conceived, i.e., the "transmission of knowledge" model:

> Constructivism. . . argues that instruction is more a matter of nurturing the ongoing processes whereby learners ordinarily and naturally come to understand the world in which they live. (Knuth & Cunningham, 1991, p. 164)

The elements of constructivist theory and their application in the classroom

The following sections describe findings from the current educational literature as to the implications of constructivism for structuring constructivist learning environments. Instructional tasks are described for each of the elements of constructivist theory listed earlier in this report. However, the order in which specific elements are discussed varies slightly from that presented earlier, in order to accommodate a more logical sequence of instructional activity.

The importance of prior understandings. Constructivism's "basic premise is that approaches to teaching and learning should begin by understanding what it is that learners *bring* to learning" (Shapiro, 1994, p. xiv). The first task in building a constructivist learning environment, then, is to uncover and work from students' existing understandings. Gathering information about students' prior knowledge helps teachers in two ways: They can capitalize on students' interests, and they can structure learning problems that effectively challenge and build on students' knowledge and experience (Brooks & Brooks, 1993; Duit, 1995; Wheatley, 1991).

Brooks and Brooks (1993) point out that "teachers' ability to uncover students' conceptions is, to a large degree, a function of the questions and problems posed to students" (p. 65). Teachers must "probe the student's knowledge deeply," continuing to ask "'Why?' 'What do you mean?' 'What does that mean?' 'How do you know that's true?' again and again" (Barrows, 1988, p. 6).

Relying on the results of achievement or intelligence tests or students' grades from previous classes will not lead to the kinds of awareness needed to support constructivist learning environments. To gain useful information it is necessary to move beyond general perceptions of students' cognitive levels or abilities:

> Categorizing students' general abilities does not help teachers in developing appropriate instructional strategies for particular topics and concepts. . . We don't know what ideas are within students' reach unless we do something specific to find out. (Brooks & Brooks, 1993, pp. 71-72)

Listening to students and observing the ways in which they go about solving problems are key to understanding them. The structures for instruction and interaction that characterize most classrooms, however, make these apparently simple tasks considerably more complicated (Schifter, 1996). Posing problems and asking questions that uncover students' understandings and methods of reasoning, providing adequate time for in-depth dialogue, and helping students to feel comfortable in revealing their existing ideas — these activities are not common to traditional instructional approaches.

As for tailoring learning problems to address student interests, this is an area in which constructivist approaches are sometimes criticized. Brooks and Brooks (1993) observe, "Critics contend that the constructivist approach stimulates learning only around concepts in which the students have a pre-kindled interest." They argue, in contrast, that "relevance can emerge through teacher mediation" (p. 35). It is possible to help students become interested in problems or topics to which they have not previously been drawn, by providing linkages to students' lives. To do so, however, still requires the teacher to be knowledgeable about students' perspectives, interests, and experiences.

Learning as an adaptive activity. In constructivist learning environments, teachers encourage a view of knowledge as understandings that can be put into action, rather than as received "truth." As Knuth and Cunningham (1991) describe it, instruction should "reveal the constructedness of knowledge, that any 'truth' begins with a set of untested assumptions that can be examined to evaluate the adequacy of the position taken" (p. 169). As part of this perspective on the nature of knowledge, teachers foster and support students' own understandings rather than imparting answers (Duit, 1995).

Perhaps the most difficult task in organizing constructivist learning environments, however, is reaching a useful accommodation between supporting students in reaching their own understandings and steering them toward an accepted body of knowledge, i.e., the required curriculum. Wood (1995) observes:

> The intuitive ideas that students hold are highly compatible with their everyday experiences. . . But from an adult point of view, these intuitive ideas constitute major misconceptions that, if allowed to persist, hinder students' scientific development. . . Teachers necessarily want to encourage students to make constructions that are personally meaningful, and yet recognize that they must also construct ideas that are acceptable to the wider society. (p. 337)

For students to learn more than the accepted answers that will assure success in the context of schooling, they need to struggle for themselves, and to attribute value to their own understandings. Wood, Cobb, and Yackel (1995) describe the experience of an elementary mathematics teacher who sought to establish a constructivist learning environment in her classroom:

> As the project teacher began to resolve her conflict of accepting children's incorrect answers, she discovered that allowing children to express wrong answers led to more fruitful discussions as students explained and justified their answers. . . When she steered their responses by leading them through the solution step by step, she realized she had taken *thinking about* the activity away from the children. In response, they stopped listening and paying attention. (p. 419)

In constructivist learning environments, instruction begins with the introduction of a problem rather than with the explanation of a concept, theory, or set of facts. As Duit (1995) explains:

> Only after students have become familiar with the view of their classmates, and thereby also have become more aware of their own view, is the scientific point of view introduced by the teacher as an alternative. Discussions take place as to how this view is different from the students' view, what the limitations and advantages of both views are, and the way in which the scientific view [may be] more adequate and fruitful than the students' view. (p. 279)

As students explore, formulate, test and express their own ideas, the activity of the classroom mirrors the processes through which scientific knowledge is developed in society. "Scientific knowledge" as used here refers not to the specific disciplines of science, but, as Knuth & Cunningham (1991) put it, "more generally to the notion of science as conventionally defined systems and processes of knowledge. . . Scientific knowledge may be contrasted with practical knowledge that a child develops through informal, everyday experience" (p. 175).

Knowledge as constructed. Fosnot (1992) states that "learning is always a case of building with, and from, initial assimilatory structures. Only through challenges to these structures, will gaps, insufficiencies, or contradictions become apparent to learners — thus facilitating reflective abstraction and accommodation" (p. 171). In an instructional setting, the "challenges" to which she refers take the form of learning problems.

According to some critics of constructivism (e.g., Merrill, 1992), an "extreme" constructivist perspective forbids teachers from pre-specifying specific curricular goals or instructional content. Following the constructivist perspective to its logical extreme, these critics argue, learning problems can be geared only to student interests, and students' explorations of those problems cannot be limited. However, as Bednar et al. (1992) respond:

> We are not arguing that there can be no specification of relevant domains of information. We can and must define a central or core body of information; we simply cannot define the boundaries of what may be relevant. (p. 23)

In-depth exploration of a smaller number of ideas and related facts, rather than the broad but rather superficial coverage common to current instructional practice, allows greater opportunity to tap student interests and sustain the opportunity for learning (Brooks & Brooks, 1993; Loucks-Horsley, Kapitan, Carlson, Kuerbis, Clark, Nelle, Sachse, & Walton, 1990). Focusing in depth on "big ideas" allows for the kinds of extended exploration, testing, and reflection that support meaningful knowledge construction.

Within the framework of the "core body of information" students are expected to learn, teachers pose learning problems that allow students to explore these central ideas and construct, discuss, and evaluate their own explanations. During this process, as noted in the preceding section, the teacher encourages students to express their ideas and refrains from characterizing them as "right" or "wrong."

Duffy and Cunningham (1996) list two "guiding forces" in developing useful learning problems: "First, the problems must raise the concepts and principles relevant to the content domain," that is, the intended curricular content, and second, "the problems must be real" (p. 193). Other authors also discuss the need to pose problems that "take place within the zone of proximal development" (a

Vygotskian concept), that is, "just a bit beyond what the child knows already, but not so far that the child cannot learn when provided appropriate guidance" (Harris & Pressley, 1991, p. 392).

With learning organized around problem solving, the teacher's role changes from that of transmitter of knowledge to one of facilitator or coach:

> The facilitator models higher-order thinking by asking questions that probe students' knowledge deeply. . . The facilitator's interactions with the students remain at a metacognitive level, and he or she avoids expressing an opinion or giving information to the students. (Duffy & Cunningham, 1996, p. 194)

A number of authors are careful to distinguish between discovery learning in which students explore freely in an unstructured environment, and constructivist learning environments, in which teachers help to guide activities, not by providing answers or steering students toward them but by asking questions that help students to examine their ideas more deeply and productively. Schifter (1996), in describing an instructional activity based on constructivist principles, observes that "the central feature" of the lesson "was neither the problem [the teacher] posed nor the specific questions she put, but rather the nature of the discussion that her students engaged in — and which she skillfully guided" (p. 496).

In helping students work through problems, the literature indicates that teachers need to provide both for action — exploration, trial and error, and application of new understandings — and for reflection. As Duit (1995) warns, "It is necessary to be cautious concerning the idea of students being active. The activity has to be in the heads of the students" (p. 281). Reflection can take a variety of forms, from dialogue to drawing to journal writing. As part of the reflective process, students learn to assess their own progress in understanding. Ackerman notes that "constructivist teachers. . . need to help the group of learners as a whole become its own critic" (p. 342).

Resistance to change. In requiring that learning problems be "real," Duffy & Cunningham (1996) are addressing two elements of constructivism: the situatedness of learning (see below), and the learner's tendency to resist changing deeply entrenched understandings. For a learning problem to effectively challenge students, it must have some meaning for them. Otherwise, as Powell (1994) describes it, students are likely to find ways to hold on to their beliefs while attempting to satisfy the teacher:

> They may construct ideas that seem to allow for both their own and the school's interpretation. Alternatively, they may compartmentalize their views of the world with one view for school and another view for the outside world[,] both kept separate and co-existing in the student's mind. (pp. 83-84)

Researchers also caution that students often do not appear to recognize contradictions that seem readily apparent to the teacher (Duit, 1991, 1995). It is often necessary to provide more than a single problem, or more than a single trial in the effort to solve a problem, to effectively challenge students' beliefs. Duit (1995) gives as an example an experiment by a 12-year-old student in which she tries to determine whether a cube of ice will melt faster if it is covered by a piece of wool or by a sheet of aluminum foil:

> The girl believes that the ice will melt first if it is covered by wool. Her argument is that wool is warm, and therefore it will make the ice warm. Of course, her ice block covered with aluminum foil melts first. But this empirical event does not shake her conviction that she holds the right view. She thinks that some sort of condition of the experiment is responsible for the unexpected outcome. . . One single piece of empirical counter evidence will usually not change students' conceptions, but many such pieces of evidence are necessary and a new conceptual framework has to be provided in which the correspondence may be explained. (p. 281)

Learning as situated. Effective constructivist learning environments provide rich contexts for learning (Brown, Collins, & Duguid, 1989). This involves posing learning problems that students find meaningful, that require the application, rather than mere acquisition, of concepts and information, and that are not so simplified that students cannot apply their learning. Bednar et al. (1992) observe that

> An abstract, simplified environment (school learning) is not just quantitatively different from the real-world environment but is also qualitatively different. . . We must *maintain* the complexity of the environment and help the student to understand the concept embedded in the multiple complex environments in which it is found. (p. 26)

Wood, Cobb, and Yackel (1995) also express concern about the artificial nature of traditional school learning environments. They cite a study in which researchers presented an arithmetic word problem to both first and third graders. The researchers "found that first graders typically attempted to make sense of the problems, whereas third graders either added or subtracted the numbers in the problem on the basis of superficial syntactic cues" (p. 403). By the third grade, students had learned to identify word problems as relevant only to schooling, and to seek the answer they thought the teacher wanted to hear.

Duffy and Cunningham (1996) describe the "question of context [a]s really a question about what aspects of the context must be represented if the learning (knowledge) is to be used. . . in other contexts" (p. 179). One strategy that helps with transfer, according to Brooks and Brooks (1993), is to "organize information around conceptual clusters of problems, questions, and discrepant situations," presenting ideas and problems "holistically rather than in separate, isolated parts" (p. 46). Similarly, Bransford, Sherwood, Hasselbring, Kinzer, and Williams (1990) recommend a strategy they call "anchored instruction":

> Anchored instruction begins with a focal event or problem situation that provides an anchor for students' perceptions and comprehension. Ideally, the anchor will be intrinsically interesting and will enable students to deal with a general goal. . . that involves a variety of related sub-problems and sub-goals. Effective anchors should also help students notice the features of problem situations that make particular actions relevant. (p. 123)

Role of social interaction. In constructivist learning environments, dialogue — both student-to-student and student-to-teacher — is a pre-eminent instructional tool (Duffy & Cunningham, 1996; Schifter, 1996): "It is primarily *through* dialogue and examining different perspectives that students become knowledgeable, strategic, self-determined, and empathetic" (Tinzmann, Jones, Fennimore, Bakker, Fine, & Pierce, 1990, n.p.). Student conversation is not incidental to, but a substantial proportion, of instructional activity. This includes student talk as they work in pairs or small groups to solve problems, small- or large-group discussion of problem-solving strategies, findings, difficulties encountered, and possible alternative solutions (Brooks & Brooks, 1993). The goal of group work from a constructivist perspective "is to share alternative viewpoints and challenge as well as help develop. . . alternative points of view" (Duffy & Cunningham, 1996, p. 187).

Providing opportunities for extended student dialogue involves assuring that all voices are heard and respected, and that students feel safe in voicing opinions that may not be "correct" from a traditional standpoint. It is particularly important to treat errors as opportunities for learning — a different strategy than what occurs in traditional instruction. As Labinowicz (1980, quoted in Brooks & Brooks, 1993, p. 83) points out, "a child's errors are actually natural steps to understanding." Thus Schifter (1996) describes a teacher's task as "pos[ing] questions that will lead through — rather than around — puzzlement" (p. 495). However, DeVries and Kohlberg (1990) observe that "traditional school practice abhors mistakes" (n.p.). Students are reluctant to voice opinions of which they are uncertain; in traditional classrooms, they learn quickly to remain quiet if they cannot produce the "right" answer (Brooks & Brooks, 1993).

A summary of the instructional implications of constructivist theory

In summary, the literature suggests the learning environments that most effectively support student learning — that "enable" rather than "distort" the natural learning process — will have the following characteristics:

- Teachers probe students' current understandings in depth, by structuring activities that bring those understandings to light, by providing numerous opportunities for students to express their understandings, and by listening to students' explanations of their reasons and problem-solving strategies as well as to their answers.

- Teachers seek a deep understanding of students' contexts, interests, and motivations, in order to create activities that engage students and build on their current interests.

- Teachers foster a perspective on knowledge as functional understandings that have been reached through experience, experiment, and negotiation among multiple viewpoints; the scientific process is fostered as a strategy for reaching ever-more useful and broadly applicable understandings.

- Teachers focus in depth on major concepts and "big ideas," rather than covering a broad range of information superficially and divorced from useful contexts.

- Teachers organize instruction around learning problems that pique students' interest, challenge their current understandings, set the intended curricular concepts in meaningful contexts, and allow students to explore ideas, pose interpretations or hypotheses, test their ideas, apply them in other contexts, and reflect on their learning.

- Teachers help to guide students as they work through learning problems, asking questions that lead students to examine their own ideas and reasoning processes, focusing issues, and providing access to additional information and resource materials.

- Teachers foster student dialogue as a primary instructional tool, structuring the classroom to facilitate both student-to-student and student-to-teacher dialogue, to encourage the airing of ideas and uncertainties without fear of the stigma of "right" or "wrong," and to assure the meaningful involvement of all students in classroom dialogue.

The role of technology in constructivist learning environments

Many researchers propose that technology — particularly computer-based technology — can become an essential piece of a new type of K-12 learning environment based on constructivist learning theory (Bagley & Hunter, 1992; Bransford, Sherwood, Hasselbring, Kinzer, & Williams, 1990; CTGV, 1991; Duffy & Jonassen, 1992; Knuth & Cunningham, 1993; O'Connor, 1992; Perkins, 1992; Riel, 1994; Strommen & Lincoln, 1992). For example, Sandholtz et al. (1997) state:

> Technology is a catalyst for change in classroom processes because it provides a distinct departure, a change in context that suggests alternative ways of operating. It can drive a shift from a traditional instructional approach toward a more eclectic set of learning activities that include knowledge-building situations for students. (p. 48)

According to Bagley and Hunter (1992), students become empowered and spend more time in active construction of knowledge when using technology. Technology provides more resources for student use in problem solving, thinking and reflection. Students spend more time collaborating with other students and communicating with teachers when developing technology projects. Means, Blando, Olson, Middleton, Morocco, Remz, and Zorfass (1993) note that many reformers now view technology as "a means of supporting goals related to increased student involvement with complex, authentic tasks and new organizational structures within classrooms and schools" (p. 1).

For the most part, however, these propositions remain untested. Few studies have focused specifically on the relationship between the creation of constructivist learning environments in K-12 classrooms and the role of technology in supporting those environments. Studies *have* examined the impact on student learning of particular software or particular strategies for using technology. In addition, several scholars have published theoretical perspectives and approaches to the use of technology that reflect elements of constructivism.

The following sections outline the literature on instructional technology as it relates to constructivism. The first section provides a general overview of current perspectives on the range of instructional roles for computer-based technology. This is followed by an analysis of a variety of technology applications in light of the instructional implications of constructivist learning theory presented earlier in this paper. Because the current literature focuses primarily on computer-based technology, this discussion is limited to the use of computers in combination with other hardware, software, or networks.

Perspectives on the instructional role of technology

Technology alone, of course, does not produce learning; technology is a tool that can be used in many ways, to various effect. The literature generally describes three major categories of instructional use for computer-based technologies; these are outlined below.

Learning from the technology. When technology is used to convey specific information or skills, Zucchermaglia (1991) describes it as "full" technology — full of information to be conveyed to the student. Maddux, Johnson, and Willis (1997) label applications that support this use as Type I applications, which are "designed to make it easier, quicker, or otherwise more efficient to continue teaching the same things in the same ways we have always taught them" (p. 18). Use of technology in this case mirrors traditional classroom practice: users are relatively passive, the content and interaction between the user and the software are predetermined, and there is a limited repertoire of acceptable responses. The acquisition of facts through repeated practice and rote memory, or *learning from* the technology (Jonassen, 1996), is the goal of instruction. This use of technology was the most prevalent one in the 1970s and 1980s (Jonassen, 1996).

"Full" or Type I technologies include computer assisted instruction, integrated learning systems, computer-based tutoring systems, assessment software, and administrative software, such as electronic grade books or attendance record-keeping software. Computer-assisted instruction and integrated learning systems have been readily adopted in many schools as they closely match the traditional routine of classroom life. McClintock (1992) points out that technology has often been used as a replacement for existing tools, such as books, rather than as an alternative medium through which different tasks might be performed and different objectives might be achieved.

Some researchers (Vockell & Schwartz, 1992; Merrill, Tolman, Christensen, Hammons, Vincent, & Reynolds, 1986) suggest that computer-assisted instruction can increase achievement because it leads to automaticity of lower-level skills through extended practice. A computer that is endlessly patient with the learner monitors this practice. In the tutorial form of computer-assisted instruction, the computer provides additional information to the learner if an incorrect answer is supplied. This continues until the learner is successful.

Literally hundreds of research studies have been conducted regarding the effects of computer-assisted instruction (CAI). From his analysis of twelve meta-analyses of the effectiveness of computer-based instruction programs developed primarily prior to 1990, Kulik (1994) concludes that students usually learn more and in less time with computer-based instruction. Becker (1992), however, found numerous methodological problems with many studies that have demonstrated positive effects of using CAI. In his meta-analysis of 100 studies, he concludes that differences in CAI users and non-users are too small to have educational significance.

Technology as the object of instruction. Another use of technology in schools that exemplifies traditional learning environments includes learning *about* the technology itself (Jonassen, 1996). Classes in computer programming and computer literacy are designed to teach students how computers work. Students learn specific skills related to using the computer, such as keyboarding skills, ethical uses of computers, or a particular programming language, but these skills are not tied to other content. These classes were prevalent in the 1980s, but Jonassen (1996) observes that this use of technology is now less emphasized in schools. He attributes the change to:

- the increasing availability of computers in society that gives students more experience with them outside of schools;
- the understanding that one does not have to know how a computer works to take advantage of it as a tool; and
- the emphasis on memorizing vocabulary about computers in computer literacy classes, which had little applicability to educational goals of schools.

Learning with technology. Learning *with* technology drives much of the current thinking about the use of technology to support learning (Jonassen, 1996). Bonk, Hay, and Fischler (1996) note, "Currently popular ideas about students using electronic tools to be designers of knowledge are akin to Dewey's arguments that children must actively construct and interrelate knowledge by learning in more authentic ways" (p. 95). According to this perspective, when technology becomes an integral part of the classroom learning environment it provides a tool for both teachers and students that can facilitate new roles and new instructional strategies.

Technology used as a tool can serve as a means to seek and process information, and to reflect on one's understandings, beliefs, and thinking processes. Used in this way, technology is "empty" as it allows the learner to enter information and explore new content relationships (Zucchermaglia, 1991). Ordinary application software such as word-processing, spreadsheet, graphics, presentation, and database software; problem-solving software; simulations; electronic mail; and the Internet are technology tools that fit into this category. These applications, labeled Type II by Maddux et al. (1997), give the user control of almost everything that happens, including the interaction between the user and the machine. An extensive repertoire of acceptable responses is provided for. Rather than rote memorization of facts, Type II applications encourage the accomplishment of creative, higher-level tasks (Maddux et al. 1997).

Because of the interactive nature of technology and the power of its information-processing capabilities, Jonassen (1996) proposes that when students *learn with* technology, it becomes a "mindtool." He defines mindtools as "computer-based tools and learning environments that have been adapted or developed to function as intellectual partners with the learner in order to engage and facilitate critical thinking and higher-order learning" (p. 9). Using commonly available software (databases, spreadsheets, electronic mail, multimedia, hypermedia, and others), learners employ technology to both construct and represent knowledge. This concept is similar to Pea's (1985) conception of a cognitive technology as " . . . any medium that helps transcend the limitations of the mind, such as memory, in activities of thinking, learning, and problem solving" (p.168).

Learning with technology and the instructional implications of constructivism

In a constructivist learning environment technology plays an acknowledged and purposeful role in the day-to-day activities, but does not become the object of instruction (McClintock, 1992). According to its advocates, this environment can provide students with a complex laboratory in which to observe, question, practice, and validate knowledge. The following discussion examines how technology can be used to support the creation of classroom environments based on the instructional implications of constructivist learning theory. This discussion is based on the premise that it is learning *with*, not *from* or *about*, technology that makes computer-based technologies important tools in a constructivist learning environment.

Probing students' prior knowledge, understandings, and interests. Basing instructional approaches on constructivist learning theory suggests that teachers must understand what learners bring to the learning situation and begin there in helping students build new knowledge. Basic, Type II applications offer tools to help with this process. For example, students can use word-processing software or e-mail to share their understandings with student peers as well as teachers. These uses of technology have been demonstrated to improve writing skills, produce more and better ideas for decision making, and increase motivation (Center for Applied Special Technology, 1996; Chun, 1994; Cohen & Riel, 1989; Honey & Henriquez, 1996; Mabrito, 1992; Moore & Karabenick, 1992 Naiman, 1988; Olaniran, 1994).

As Means and Olson (1997) note

> Technology can help to make students' thinking processes more visible to the teacher, something that does not happen when students simply turn in a completed assignment for checking and grading. As teachers observe their students working with computer applications, they can see the choices each student is making, stop and ask about the student's goals, and make suggestions for revisions or different strategies (p. 126 - 127).

One technology particularly suited to this process is Computer Supported Intentional Learning Environments (CSILE), developed by researchers at the Centre for Applied Cognitive Science (Ontario Institute for Studies in Education). CSILE is a software-based tool that provides a means for students to build a collective database (knowledge-base) of their thoughts, in the form of pictures and written notes. CSILE stores the thoughts entered by each student and makes them available for everyone . . . The system is a form of hypermedia that allows notes entered as text, drawings, graphs, and timelines to be retrieved, linked, commented on, rated, and so forth. (Scardamalia, Bereiter, McLean, Swallow, & Woodruff, 1989, p. 52)

Students enter what they already know about a topic at the beginning of the creation of a CSILE database. This provides a tool for the teacher to both identify prior knowledge and document the process of knowledge construction. Using CSILE, students can create and label written notes in a variety of ways. The labels are encouraged "in order to facilitate reflection and to allow the notes to reappear in multiple contexts. In addition, written notes can be placed on a timeline, or attached to a spot on a picture" (Scardamalia et al. 1989, p. 52).

Knowledge mapping software (such as Inspiration™) is designed to capture and organize brainstorming and idea generation sessions into concept or knowledge webs. This is a useful technology to help teachers uncover students' existing knowledge about a topic. For example, the teacher can pose a problem or suggest a content topic to students. Using the software, students can create a diagram of ideas, consisting of one or a few words, connected by "links," which may be lines or arrows or a text label. These webs of ideas may be linked to other webs, links may be changed easily, and notes may to be added to each idea in the web. All of these elements may also be converted to an outline format (Neuburg, 1997). As the teacher examines the webs or diagrams created by students, a visual representation of their prior knowledge is available for analysis.

Hypertext and hypermedia may be used by students in a like manner for assembling and linking information to present their understanding of almost any topic. Hypermedia is software built on non-linear interrelationships among text and other elements. When text is linked to related text using programming commands, it is called hypertext. By adding elements that allow the user to move through text, images, and sound, a hypermedia environment is created. Hypertext and hypermedia are structured so that the user accesses information in ways that are meaningful to him or her (Jonassen, 1996) rather than through a linear presentation. As students create hypermedia stacks, their existing knowledge is represented.

Simulation software also offers an opportunity for uncovering and examining student prior knowledge. "Simulations put the student in an active role in an environment that has a set of rules" (Maddux, et al. 1997, p. 219). As a student begins to interact with a simulation, prior knowledge guides the choices s/he makes when selecting from the options offered. Simulations such as *The Would-Be Gentleman* require the user to choose strategies designed to increase her/his social mobility in France during the reign of Louis XIV. Maddux et al. (1997) note that "players find it difficult to success if they do not have considerable knowledge of the period" (p. 219). Observing the choices made as the student begins the simulation and discussing the reasons for those choices provides a rich opportunity for both the teacher and the student to explore the student's prior knowledge.

In addition to the prior knowledge and understanding students bring to the learning situation, they also bring interests. As noted previously, teachers who create learning environments that enable the learning process structure activities that build on students' current interests. Technology can be used to help identify those interests. Allowing students to create hypermedia stacks or to use knowledge mapping software to create idea webs about self-selected topics can provide teachers a clearer picture of students' interests.

Once student interests and prior knowledge are identified, teachers guided by constructivist learning theory base learning experiences on both. Often, however, teachers cannot respond to the multitude of student interests due to lack of resources available in the classroom or the school. Technology can provide access to resources that build on students' interests (Irving, 1991; Riel, 1994; Swan & Mitrani, 1993). Databases of information available on CD-ROM or on the Internet, however, allow students to examine a multitude of topics that may be of unique interest to an individual student (McDaniel & McInerney, 1992).

Means and Olson (1997) found technology can support teachers' efforts to engage students in long-term, complex projects by dramatically enhancing student motivation and self-esteem. Numerous other studies have demonstrated the increased motivation and engagement of students when they use technology (Brownlee-Conyers & Kraber, 1996; Dimock, 1996; Deal, 1995; Ferneding-Lenert & Harris, 1994; Harasim, 1989; Lowry et al. 1994; Mason, 1989; Moore & Karabenick, 1992; Ross et al. 1990; Ryser et , 1995; Sandholtz et al. 1997; Velayo, 1993; Williams, 1995). One study, focused on students with limited English proficiency (LEP) who used videodiscs as part of instruction over a three year period, reported that these students had significantly stronger agreement with statements such as: "I like my science class," "We do fun things in science," "My friends like science," and "I would like to take more science" than LEP students in conventional classrooms (Barrutia, Bissell, Rodriguez, & Scarcella, 1993).

Learning as an adaptive activity. As noted previously, in constructivist learning environments instruction should begin with the introduction of a problem. Students must struggle to come to individual understanding that can be put to use in the particular context of solving that problem. Teachers are charged, however, with ensuring students master a core body of knowledge. Some studies suggest that technology can be a useful tool for teachers in balancing the need to support students as they reach their own unique understandings and the need to specify core curriculum for students to learn. Because it is a tool that offers a multitude of means for both acquiring information and representing newly constructed knowledge, technology allows for multiple perspectives on the task at hand (Irving, 1991; Ayersman, 1996; Neuburg, 1997).

The Internet provides access for teachers and students to an enormous source of information resources and alternative perspectives. This rich source of information can form the basis for problem generation and exploration that is authentic for students (Knapp & Glenn, 1996). "Computers can deliver information which, in terms of sheer volume and complexity, takes students to the edge of their competencies in evaluation, selecting, retaining, organizing, and interpreting it" (McDaniel & McInerney, 1992, p. 76).

Technology has been used to present problems to students that are based in real-world situations, such as a fishing trip. The *Jasper Series* is a set of video-based adventures presented in a videodisc format. Each adventure ends with problems posed as questions facing the characters, such as "What's the fastest way to rescue the eagle and how long will that take?" (CTGV, 1991a, p.13). These problems have a multitude of possible solutions. "Students must engage in argumentation and reflection as they. . . attempt to make sense of alternative points of view" (CTGV, 1991a, p. 16). Because the video images are digitized on a videodisc, information embedded in the adventure story that students need for creating possible solutions may be randomly accessed to support the students' ideas about solutions.

Problem solving tools, such as spreadsheets, can provide a means to students to generate hypotheses and test alternative solutions to problems. Spreadsheets are software applications that can store information, make calculations based on that information, and present the information and the results of those calculations. Changes made in one location in a spreadsheet automatically recalculates all of the affected values in other parts of the spreadsheet. This enables the user to become "a hypothesis tester (playing "what if" games) rather than merely a calculator. (Jonassen, 1996, p. 79) Spreadsheets "help users make decisions about what actions to take if a particular set of conditions evolves. Problem solving is an important outcome of using spreadsheets" (Jonassen, 1996).

Hypermedia, described in the previous section, can also be used to foster a variety of perspectives and "right" answers. Students can create individual representations of knowledge and information about any topic. They must organize information in order to create such presentations. Riddle (1995) found that students using hypermedia demonstrated increased ability to convey insight and individuality, greater descriptive detail, and unique perspectives.

Knowledge as constructed. Teachers operating from constructivist perspectives provide opportunities for students to conduct in depth exploration of a smaller number of "big ideas" within the framework of the core body of knowledge students are to learn. Means & Olson (1997) found technology increased the complexity with which students could deal successfully and created a multiplicity of roles, leading to student specialization. It allowed in-depth exploration of a smaller number of ideas and related facts around authentic, challenging tasks. They noted:

> When students are using technology as a tool or a support for communicating with others, they are in an active role rather than the passive role of recipient of information transmitted by a teacher, textbook, or broadcast. The student is actively making choices about how to generate, obtain, manipulate, or display information (p. 125).

The Internet can promote student exploration and problem-solving. KID FORUM, a set of moderated on-line projects in KIDLINK, is an Internet-based forum for students throughout the world. One KID FORUM project, "Our Earth — My Place," allowed children from fourteen countries to share and compare information about their local physical environments (Stefansdottir & Thurber, 1996). The teachers coordinating the project noted that the shared information became increasingly complex as the yearlong project progressed. Different groups of students applied their learning in unique ways: one group designed landscaping plans for other locales, complete with budgets; another group tested local bodies of water for bacterial levels; and a third group began a local campaign for recycling motor oil. Here students drew upon distributed expertise, solved problems, and collaborated with many peers to construct knowledge.

Databases are another technology that provides opportunities for such active learning, according to Jonassen (1996).

> The process of creating and manipulating a database is inherently constructive, which means that learners are (mentally) actively engaged in learning rather than merely reading or responding to questions. They are actively building knowledge structures, because they are actively engaged in knowledge representation activities. [Learners can] also try to arrange the information in ways that may make more sense to them (p. 65)

Scardamalia & Bereiter (1991) propose that CSILE, a database software described earlier, shifts the source of questions in the classroom to students, rather than the teacher, increasing the opportunities for students to construct new and more in-depth knowledge.

Constructing computer-based idea webs using knowledge-mapping software can engage learners in

- the reorganization of knowledge
- explicit description of concepts and their interrelationships
- deep processing of knowledge, which promotes better remembering and retrieval and the ability to apply knowledge in new situations
- relating new concepts to existing concepts and ideas, which improves understanding (Fisher et al. 1990, cited in Jonassen, 1996, p. 95)

Hypertext and hypermedia may also be used as tools by students for exploring, assembling and linking information to develop and present their understanding of almost any topic. Ayersman (1996) notes that there is limited research on learning with hypermedia as a tool in K-12 environments. Based on what is available, however, he found that the use of hypermedia applications promoted deep comprehension and enhanced listening comprehension, story production and decoding skills (Mayfield-Stewart et al. 1994) and improved ability to discover links among people, places, events and issues within historical contexts (Swan, 1994).

The Jasper series described earlier offers another example of technology-based learning problems that appear to support instruction based on constructivist theory. Researchers explain, "The idea of building an understanding of the need for further learning is very important for the Jasper series. The adventures are designed to create 'teachable moments' that can lead to the meaningful acquisition of new knowledge" (CTGV, 1991a, p. 28). When teachers use the Jasper series, "there is marked improvement in their students' abilities to generate the classes of sub-problems that need to be considered in order to solve complex problems" (CTGV, 1991a, p. 29). Studies (CTGV, 1991b) also reveal that students:

> gained confidence in their abilities to deal with complexity,
> observed that they were forced to think and work "harder" than in typical mathematics classes, and
> found math more fun and meaningful (p. 17).

Geometric Supposer is software that provides opportunities for "making and testing conjectures in geometry through constructing and manipulating geometric objects and exploring the relationships within and between those objects" (Schwartz & Yerushalmy, 1987, cited in Jonassen, 1996, p. 245). Students can make a conjecture and easily test it "by asking *Geometric Supposer* to measure the angles or by applying the relationship to several other triangles." The student will learn immediately whether a conjecture is true or not.

To encourage the construction of knowledge, teachers should provide opportunities for reflection. Conscious reflection upon what is being learned, how it relates to what is already known, and how learning occurs helps learners question personal perceptions of reality and facilitates the analysis and acceptance of the perceived realities of others (Bielaczyc, Pirolli, & Brown, 1995; Forman & Pufall, 1988). Maddux et al. (1997) describe the importance of class discussions and debriefing after working with software such as *Geometric Supposer*:

> Debriefing is especially important with simulations. During the debriefing phase, a discussion of the issues students dealt with in the simulations often helps them consolidate the concepts and procedures they learned. Debriefing also helps students identify misconceptions or inaccurate assumptions about the simulation and provides an

opportunity for students to discuss the differences between simulation and reality (p. 233).

Technology can also provide a medium in which feedback may be received, input solicited, or thinking recorded. Student electronic portfolios are one example of how technology can provide for additional opportunities for self-reflection and self-assessment (Falk, 1996; Strommen and Lincoln, 1992). Multidimensional portfolios (Jonassen, 1991) that include collections of student work can illustrate the process of learning through a variety of products (Falk, 1996). Electronic portfolios created in hypermedia can even be used to document a student's progress as s/he progresses through grade levels, providing a manageable document of text-based and visual work (Brewer and Kallick, 1996).

As noted previously, the role of teachers in a constructivist learning environment shifts to one of facilitation of the learning process rather than the traditional role of information provider. Computer-based technologies offer incentives and strategies for teachers to shift their role from expert provider of "right" answers to facilitator or coach. This does not minimize the teacher's role in the least, however, as technology can assist the learner in constructing meaning only through meaningful and purposeful interactions. Teachers remain the pedagogical experts in the classroom and as such are the key to obtaining successful interaction (Mehlinger, 1996; Sandholtz et al. 1997; Sivin-Kachala & Bialo, 1997).

In their study of a range of instructional technologies, Means and Olson (1997) found that technology gave teachers additional impetus to take on a coaching and advisory role, perhaps because, as noted previously, students learn to use the technology must faster than teachers. Functioning as a facilitator with regard to technology can also lead to teachers' willingness to assume a facilitative role with regard to content (Sandholtz et al. 1997). When this happens, students develop "a greater sense of ownership in the process of instruction" (Sandholtz et al. 1997, p. 80). They also begin to ask for more opportunities to play the role of peer tutor (Sandholtz et al. 1997) and increase their ability to self-regulate their own learning (Means & Olson, 1995).

Hypermedia applications can also encourage teachers to take on a facilitative role (Ayersman, 1996). Using CSILE, for example, students gradually become less dependent on the teacher to direct discussions. As students develop skill in posting ideas, commenting on the ideas of others, and posing questions about the ideas in the group's knowledge base, teachers take on a more facilitative role. Scardamalia and Bereiter (1991) found that about half of the questions posed by students when using CSILE were classified by their teachers as questions around which the teacher believed s/he could "profitably be engaged along with the students in research" (p. 66).

Resistance to change. A key tenet of constructivist learning theory is that learners hold on to prior understandings and are unlikely to change those ideas. As noted previously, even when a physical demonstration that challenges existing ideas is observed by the learner, s/he tries to hang on to old beliefs. Many opportunities to test existing knowledge in a variety of ways during problem-solving activities are needed. The problem situations provided must be real to the students, effectively challenge their existing understandings, and offer multiple opportunities to test their old ideas against emerging ideas. While working through these problems, students need opportunities to explore, test, apply, and reflect on their understandings in order to increase the opportunity for learning to occur.

Technology appears to have particular potential for structuring such learning problems and supporting multiple trial opportunities. Through the use of microworlds, simulations, virtual environments, and links to resources that extend well beyond the classroom, teachers expand their options for creating problems that engage students' interests, provide complex, multi-level challenges, and offer rich, meaningful contexts for application (Bednar, Cunningham, Duffy & Perry, 1992).

Students existing ideas are challenged when they can manipulate variables and observe the effects of those manipulations on physical objects. Subsequent hypotheses based on observations may then be tested, providing further opportunity for challenging student ideas. Technology may provide for this process through microworlds. This software is similar to simulations but limited to exploration of conditions that exist in the real world. One such microworld, *Interactive Physics*, allows students to explore "topics in Newtonian mechanics, such as momentum, force, and acceleration. . . Each experiment. . . simulates a physical phenomenon, allowing the learner to easily manipulate several attributes of the world, such as gravity, air resistance, elasticity of bodies, and various surface parameters" (Jonassen, 1996, p. 241).

Virtual environments create a context different from classroom experience. The graphically constructed or physically represented context is believable and real to those who use it. An example is the software *Spatial Algebra*, which exposes students to visual and auditory information that might be used in authentic situations. Although objects are virtually manipulated, the familiarity of the easily recognized objects allows the user to interact intuitively with the program. Students can manipulate objects as they would be manipulated in the real world but they can also manipulate objects in ways that *cannot* be accomplished in the real world. *Spatial Algebra* also allows learners to return to previous locations, review, and practice as they build more sophisticated understanding. This provides a means for the multiple trials often needed for students to recognize contradictions between their existing knowledge and what they are observing (Duit, 1995). In a traditional classroom, although the learner can review textual material, it is not so easy to recapture the immediacy of the learning experience (Winn & Bricken, 1992).

Scientific visualization software, used by practicing scientists, can incorporate large quantities of data to represent entire phenomena using color, shape, and animation to show progression over time. High-speed computation capacity is required to use such environments. Edelson, Pea and Gomez (1995) propose that these tools allow learners to understand abstract scientific concepts formerly considered too complex for high school students. Three scientific visualization softwares, the Weather, Climate, and Greenhouse Effect Visualizers, were developed as part of the Learning Through Collaborative Visualization (CoVis) Project. Each of these tools allows students to plan for identification and application of appropriate data, visualize and manipulate data, explore student-generated questions, and create artifacts to demonstrate their findings. Because students can test and retest hypotheses about natural phenomena and changes in the environment that result over time using these softwares, existing notions about weather, climate, and the greenhouse effect may be challenged.

Simulation software and hypermedia environments also allow data to be examined and re-examined, giving the learner the ability to manipulate the situation to test hypotheses. A much-used program that simulates real-world contexts is *SimCity*, which allows users to manipulate physical features and environmental conditions as they design a city. *SimCity's* design provides the user with basic information while allowing creation of a functional city plan based on input from the user. The software simulates situations that would result from the student-developed plans, including fires blazing out of control or a city overrun by garbage if no fire station or garbage collection was provided for in the design. Students initial development of a city plan is typically based on their existing knowledge of these environments. Testing the results of a city created on this knowledge challenges students ideas and pushes them to learn more about what is necessary. Posing the problems as a result of student-generated plans makes the solutions meaningful for the students, rather than looking for a solution they believe to be what the teacher wants (Powell, 1994).

Computer probeware, more formally called Microcomputer-Based Laboratory (MBL) consists of "probes" that are used to measure physical properties such as heat and light. The software used with the probes records, analyzes, and displays these measurements on the computer screen. Using probeware, students can conduct "hands-on experiments with equipment that is often easier to use, safer, and more precise than traditional laboratory equipment" (Knapp & Glenn, 1996, p. 116). Initial measurements and the resulting changes can be observed on the display screen as they occur, making the results more distinctive and easier to understand.

Knapp and Glenn (1996) go on to report the results of experiments conducted by group of students using probeware to determine if a golf ball, basketball, and tennis ball released at the same time would hit the ground at the same time. As was the case with adult learners noted previously, students reported they saw the balls land at different times. Using the computer and a light probe, students conducted the experiment again and were able to measure exactly when the objects landed -- all landed at the same time. The researchers report that the discussion following the experiments was crucial to learning *with* the computer.

> The experiment was finished, but the class discussion was not. Students wondered why a feather or a piece of paper would not hit the ground at the same time as the balls. Someone suggested that they flutter . . . something holds them up. What is it?...air, they realize. . . . This experiment showed them that the computer's ability to measure accurately is significant. Yet, if they had looked only at the experimental data, they could have assumed that a feather would land along with the balls. From this teacher-guided experience, they learned that a human's ability to think about things, make comparisons, and come up with revised theories is crucial. (p. 117)

Learning as situated. Many of the applications of technology above involve the replication of "real world" contexts in which students can explore problems, generate and test hypotheses, and construct knowledge. "Simulations offer students the opportunity to confront problems and make decisions in an imaginary environment that is realistic enough to provide meaningful issues and appropriate consequences." (Knapp & Glenn, 1996, p. 29)

Means & Olson (1997) note

> When technology is used in support of challenging projects, it in turn can contribute to students' sense of authenticity and to the "real-life" quality of the task at hand. As one teacher put it, students need to feel that they are "using real tools for real purposes." Being able to access the tools that are used by professionals for similar tasks allows students to aspire to a level of work and quality of product that more closely reflects what they see and know of the outside world. (p. 121)

E-mail may be used to provide a medium for written communication that is embedded in an authentic context, that of exchanging ideas and information with distant peers or tutors. Either e-mail or word-processing software may be employed to enable students to write for a real audience, such as peers or community members about topics that affect them (Maddux et al. 1997). Having an authentic purpose, context and audience is cited as responsible for improved skills in writing, reading, and critical thinking (see Schwartz, 1987; Cohen and Riel, 1989; Jenkinson, 1990; Gallini and Helman, 1993).

Hypermedia allows users to enter virtual environments that include text, sound, visual images, animation, and video. These elements may be randomly accessed through choices made by the learner, rather than a pre-ordained sequence created by the software designer. Honebein, Duffy, & Fishman (1991) note that, through simulation, their hypermedia environment, the Lab Design Project

> provides an environment for learning that is richly detailed and situated in a meaningful context. The environment provides a level of complexity and information representative of the actual setting, the

> tasks and activities the students engage in are consistent with the authentic activities of expert sociologists, and the tasks are meaningful to the learners' own research interests. Learners are able to apply and practice the same problem solving skills in accomplishing the task as if they had been in the actual environment. They are also more readily able to transfer those skills to an actual environment (p. 102).

Teague and Teague (1995) describe a learning experience for seventh-grade social studies students who were interested in their local township's master plan. A county planning and zoning representative visited with students and explained city development and the processes involved. Then students were introduced to *Sim City*, a simulation described in a previous section. After learning the software, teams of four to five students collected data and discussed decisions. The teacher provided feedback on the scope and depth of their plans and directed them to other resources when necessary. Members of the local planning and zoning commission reviewed the students' plans and students explained and justified their reasoning to the experts. Although the program could not mirror all the variables that exist in actual city planning, students used mathematical, economic, government, environmental, demographic, and architectural knowledge as they constructed a "big" picture of the development of a city in a flexible and responsive learning environment. The real-world context of the students' own community effectively supplemented an electronic one (Teague & Teague, 1995). There was evidence that students were motivated by the relevance and realism of a task that allowed for multiple solutions.

In addition to hypermedia applications such as the ones described here, the Internet provides a rich source of outside information resources that allow students to address complex problems (Means & Olson, 1995). The Internet connects teachers and students to people outside the school environment, providing access to expertise not available locally (Harasim et al. 1996; Wighton, 1996).

Irving (1991) conducted a two-year study in six schools (one primary and five secondary) in which students were given access to on-line information services. The project was designed to stimulate students' use of a variety of information resources and the study of contemporary topics. Conclusions of the study were that "when working on topical issues, on-line services provided immediate, on-demand and up to date material not available in or near the schools, and access to specific information on topics for which school books either did not exist or were not in the school resource collection" (Irving, 1991, p. 225).

Two software-based learning environments that connect users across distance using telecommunications technologies are known by their acronyms, MUDs and MOOs. MUDs are Multi-User Domains in which synchronous, text-based conversations are carried on in simulated electronic "rooms" in which users respond to real-time text-based messages (Bruckman & Resnick, 1995; Resnick, 1996). MOOs are Multi-User Object-Oriented MUDs that expand the text-based context of MUDs by adding visual objects with which participants can interact. In these object-oriented environments, doors can be opened, chairs can be moved, and point of view can be altered. Participants can also create their own objects to add to the virtual environment (Dillenbourg & Schneider, 1995). Both MUDs and MOOs allow students to participate in virtual, authentically represented worlds. These electronic spaces can replicate real-world environments and problems in which students can test ideas and practice skills.

Multimedia technology provides access to text, audio, video, or still images of primary source material. Students learning about historical or current events are thus provided numerous options for obtaining information.

> Instead of reading about the D-Day invasion, a CD on the event lets you hear broadcasts from the front, see photographs and video from different theaters of battle, and travel from one battle area to another by clicking on a map displayed on your computer screen. New media gets you closer to an event, process or concept than most other forms of information. It can be, as an ad says, the next best thing to being there (Maddux et al. 1997, p. 205).

Social interaction. Technology can serve as a stimulus for changes in the role of the teacher and also alter the interaction in the classroom. Learning becomes a public and highly visible activity when using technology. It can support students as they build shared meaning through a collective transformation of their learning experiences (Roschelle, 1996). "In our observations of technology-using classrooms, we saw numerous examples of students acting as peer coaches for each other, offering advice when a peer had trouble. . . . Such advice giving was continual when students worked together in small groups, but was also quite common among students working individually on computers"(Means & Olson, 1997, p. 127).

Sandholtz et al. (1997), in describing the results of the introduction of technology into Apple's Classrooms of Tomorrow, observed:

> Rather than sitting quietly and waiting for their teacher to help them with the technology, students began to take the initiative and ask each other for assistance or volunteer information to one another . . . This sudden increase in peer interaction disturbed teachers . . . who were accustomed to children raising their hands for permission to speak or leave their seats (pp. 77-78).

Teachers in these classrooms gradually adapted to the increase in student interaction, and many began to allow and encourage student dialogue in relation to instructional content as well as technology (Sandholtz et al. 1997).

Many of the technology applications described previously encourage extensive student-to-student interaction as students work to explore and solve problems.

Word processing can support constructivist learning environments through changes in the social organization in the classroom. Positive effects on achievement are reported in several studies when reading and writing are no longer exercises to be graded, but rather authentic experiences for communication (see Cannings & Brown, 1986; Bruce, Michaels, & Watson-Gegeo, 1985, cited in Maddux et al. 1997).

Hypermedia also promotes small-group interactions and allows for the development of original projects reflective of group collaboration (Wilson & Tally, 1991). Ayersman (1996) concludes "having students construct hypermedia software has benefits beyond increases in performance or attitude. Students learn both content area information and social skills as they cooperate in teams to collaboratively develop hypermedia software" (p. 517).

Sivin-Kachala & Bialo (1997) note that use of collaborative technology such as interactive brainstorming and writing programs, telecommunication links, and Internet access contributed significantly to peer collaboration and less teacher direction of classroom learning. Collaboration can result in "communities of learners" for which electronic networks can support ongoing dialogues and exchange of information (Resnick, 1994; Riel, 1994; Brown & Palinscar, 1989).

Projects conducted with scientific visualization software also include provisions for dialogues with a teacher or scientist as an essential piece in helping students build functional understandings (Edelson, Pea & Gomez, 1995). Researchers combined the use of the visualizers with desktop videoconferencing and software that allows screen sharing. Scientists and teachers, serving as telementors, can comment on students' questions, hypotheses and plans to facilitate increased learning. Students can record their notes and findings electronically, allowing other students to ask questions and comment on the work as well, even when they are not in the same physical place. For example, students in Chicago studying mineralogy were mentored by scientists in San Francisco, who used questioning strategies to press students to probe more deeply into the topics they were studying (Edelson, Pea & Gomez, 1995).

Students working in teams using the Weather Visualizer entered predictions, viewed the predictions of other groups and argued for or against each forecast. During the activity, one group of students posted a "hint" about the effect of wind speed in the upper atmosphere on the rate at which weather patterns would be moving. Edelson, Pea and Gomez (1995) note:

While it was the social environment established by the teacher that led the students to share this insight, the software provided them with the means to do so, and the nature of the activity made this piece of information valuable to the students involved. In the end, small pieces of information like these, shared and contextualized through meaningful activities, are the materials out of which learners are able to construct scientific understanding. (n. p.)

As the preceding example suggests, technology can support the extension of student dialogue far beyond the classroom. The Alice/Collaborative Inquiry Testbed (Feldman & Nyland, 1994) involves the use of electronic networks as a means for students to collaboratively investigate real-world science problems. Students at a variety of sites establish shared goals; collect and share data; and share knowledge-building through organizing and analyzing the data and sharing their findings.

Students tend to generate higher level reasoning strategies, a greater diversity of ideas and procedures, and more critical and creative responses when they are actively learning in cooperative learning groups. Electronic means of communication facilitates such collaboration (Bagley & Hunter, 1992). Social interaction is a key goal and component of Electronic Learning Circles (Riel, 1996), a global project. Teachers and students from classes in diverse geographical locations collaboratively choose a learning task. Students exchange their work, receiving guidance from their own teacher, as well as teachers in other locations and the learning circle facilitator. One publication is created based on the work of all the students in the learning circle. A reflection about the activity, the product, and the learning that took place closes the learning circle.

Learning experiences incorporating telecommunications enlarge the circle of social interaction from student peers in the classroom, to students and experts across the school, the community, and even the globe. By introducing a wide variety of perspectives and increasing the dialogue about the topic of study, idiosyncratic conceptions are reduced and the possibility of learners confronting previous misconceptions, leading to the construction of new knowledge, is increased (Duffy & Cunningham, 1996).

What can we conclude regarding the potential of technology for supporting constructivist learning environments?

The examples listed in the preceding sections suggest that technology can support instructional approaches that are based on specific elements of constructivist learning theory. For the most part, however, existing studies focus on only one or two of the instructional implications described in this paper.

The literature does suggest, however, that technology can support constructivist learning environments. We have seen that when technology is used as a tool for learning, rather than the object of instruction or as the instructor, it can assist teachers as they strive to

- uncover students' prior knowledge, understanding and beliefs;
- tap into student interests and provide increased motivation for learning;
- base instruction on the posing of problems;
- provide a variety of experiences, experimentation, and negotiation of meaning;
- increase the complexity of the content;

- take on the role of facilitator;
- increase the ability of students to test multiple scenarios and thus challenge preconceived notions or misconceptions;
- increase the authenticity of the content and context; and,
- broaden the circle of social interaction to include students' peers and experts beyond the classroom, the school, the community and even their home country.

Virtually no research has been conducted that attempts a comprehensive study of the links between technology use and instruction based on all the implications of constructivism noted earlier. The closest to such a comprehensive look, perhaps, is the set of case studies conducted by Means and Olson (1995), who used a model of a learning environment based on constructivist theory that was first described by Means et al. (1993). In this environment, according to their model, activity is centered on authentic, challenging tasks. Students work collaboratively in heterogeneous groups. All students practice advanced skills, while the teacher acts as a facilitator. Students learn through multi-disciplinary curriculum and interactive modes of instruction in longer blocks of time than are traditionally provided. Progress is measured through performance-based assessment.

Based on this model, Means and Olson (1995) conducted case studies of classrooms and schools that appeared to exhibit the model's characteristics and also used technology as an instructional tool. They looked for "sites that had a history of using technology not for its own sake, but rather as a support for constructivist learning and a broader educational reform agenda"; they also sought schools that served "students from diverse backgrounds and low-income homes" (p. 28). Teachers studied reported that technology could indeed support their efforts to involve students in long-term, complex projects, by:

> adding to students' perception that their work is authentic and important,
> increasing the complexity with which students can deal successfully,
> dramatically enhancing student motivation and self-esteem,
> making obvious the need for longer blocks of time,
> creating a multiplicity of roles, leading to student specialization in different aspects of technology use,
> instigating greater collaboration, and
> giving teachers additional impetus to take on a coaching and advisory role (Means & Olson, 1997, pp. x-xi).

While these results are encouraging, a great deal more research is needed to explore the ways in which technology can support constructivist learning environments. While the study looked for systemic factors that might support the emergence of these environments, in-depth analysis of the classroom environments was limited to two classrooms at each of the nine sites. The process that teachers underwent to create the exemplar classrooms was not explored. It is important to note the complexity of the tasks of establishing constructivist learning environments, and of introducing instructional technology into the classroom. No matter what their potential effectiveness, implementing these approaches involves a number of significant challenges for K-12 classrooms.

The challenges of establishing constructivist learning environments, and using technology to support them

Helping teachers to move from traditional instructional approaches to those that attend to the implications of constructivist learning theory is an enormous task. Adding technology to the mix brings an additional set of challenges. The following sections describe some of the largest of these challenges.

Barriers to technology implementation

The implementation of technology to support constructivist learning environments faces numerous barriers. A study by the U.S. Congress Office of Technology and Assessment (1995) reports several factors that prevent teachers' adoption of technology: inaccessibility to hardware; costs of training, equipment and maintenance; complexity of applications for instruction; inadequate training and teachers' and administrators' apprehension about logistical or technical problems; few verifications of the benefits of technology; teacher accountability for effective use; the fear that children will learn less effectively; fragmentation of teaching subject matter; limited capabilities of machines; inadequate training; fear of replacement by machines; and perceptions of negative aspects of technology (for example, copyright infringement, control of student access, and privacy issues).

Lack of access to technology is especially a problem for schools that enroll primarily poor and minority students. For example, access to the Internet in instructional rooms is much lower for these schools.

Internet Access in Instructional Rooms	Percent
Schools with less than 6% minority enrollment	57
Schools with 50% or more minority enrollment	37
Schools with less than 11% of students eligible for free or reduced lunch	62
Schools with 71% or more students eligible for free or reduced lunch	39

Source: NCES, 1998

Without access to technology, teachers who serve these students cannot take advantage of the potential it offers to increase learning opportunities for students.

Teachers' resistance to change

Although most teachers seek ways of improving their practice, and many have expressed enthusiasm for constructivist and other reform-based approaches, their underlying — and often largely unconscious — beliefs about teaching and learning tend to diffuse efforts to establish constructivist learning environments (Schifter, 1996; Steffe & Gale, 1995). As Duit (1995) observes, "Conceptual change from the 'old' views of learning to the new (constructivist) views is as difficult as is changing students' intuitive conceptions" (p. 284).

Technology has the potential to expand information sources, provide for individualization, and help students and teachers make interdisciplinary connections. Teachers, however, often lack skills in using technology. As even well made plans for using technology can go awry due to technical problems, new technologies require teachers to accept unpredictability (Hodas, 1993). They must learn new skills for facilitating learning in a technology-rich constructivist learning environment that may run counter to traditional practices that direct and manage learning.

Teachers, like many others in U.S. society, tend to think in terms of a fixed body of knowledge that can be transmitted to students. As an example, Borko and Putnam (1995) cite research by the National Center for Research on Teacher Education indicating that "most novice and experienced teachers did not conceive of mathematics as a domain of human inquiry" (p. 46), but rather as a fixed set of rules and procedures. Because of the rapidly increasing amount of information accessible to learners, teachers are no longer the only deliverers of information. CD-ROMS, the Internet, and laser discs provide so much more information in so many different ways that a teacher cannot be expected to know or control the precise flow of information to the learner.

As a result, many teachers find ways of incorporating elements of constructivist approaches into their pre-existing instructional frameworks (Taylor, Fraser, & Fisher, in press). Duffy and Cunningham (1996) express their concern that teachers' basic perspectives remain largely unchanged even as so-called constructivist approaches are adopted in more and more schools:

> Our concern is that the shift is a shift in method rather than a shift in the conceptual framework underlying the method. . . We mean that while the method has moved from sage on the stage to guide on the side, the guide is still the fount of knowledge. He or she still possesses the knowledge the student is to acquire. It is a unidirectional relationship in which the student observes and mimics or follows the instructions of the coach. The coach, in turn, models the behavior or provides the answers (p. 184).

Acting on the understanding that knowledge is not a fixed set of facts or skills, but is uniquely constructed by each learner based on prior knowledge, experiences, and interests, implies that students, not the teacher, will drive the learning process.

Students' resistance to change

Students, too, have been socialized with certain expectations about schooling and success. The Cognition and Technology Group (1992) observe that:

> Many of today's students believe that (a) problems are something that are presented by teachers rather than discovered by good learners, (b) that good learners almost instantly know the answer to all problems. . ., and (c) that if they can't solve a problem in five minutes, then they can never solve it. (p. 117)

Students are often unwilling "to follow along discussion of the relative value of both their view and the scientific view. . . Instead they want to know what is the right — the correct view" (Duit, 1995, p. 279). As noted earlier, many students are reluctant to voice opinions that may be considered incorrect. Helping students to become comfortable with new instructional mores and approaches, then, is not always a simple or short-term task.

When technology supports the creation of constructivist learning environments, student roles change. Students often become peer mentors and mentors for their teachers as well. Some teachers' discomfort with this role shift is certainly communicated to students. As noted in the discussion of the ACOT project earlier in this paper, students also need help in learning how to function in these roles. In addition, managing student behavior takes on additional elements. Teachers often find that students who are off-task in regular learning environments may also be off-task in constructivist learning environments that incorporate technology. Issues such as abuse of expensive equipment and access to unacceptable material available on the Internet are real ones for teachers and schools as they change their practices.

The dilemma of "right" answers versus student understandings

As noted earlier, one of the central dilemmas in establishing constructivist learning environments is addressing the question posed by Ackerman (1995): "How can a teacher give reason to a student. . . by appreciating the uniqueness and consistency of his or her thinking, while, at the same time, giving right to the expert whose views coincide with more advanced ideas in a field?" (p. 341) Even if they wanted to, teachers cannot abandon the prescribed curriculum; at all levels, national, state, and local, the U.S. educational system demands that students learn, or at least be exposed to, a substantial body of information.

The demands of the system thus interact with teachers' preconceived beliefs about the nature of knowledge, learning, and teaching. The result is instruction that, while allowing students to be more active and "hands on" in the classroom, maintains the traditional "transmission" model of instruction. As Duit (1995) describes it, lessons, even those seeking to use a constructivist approach, "try to guide students to the same conceptions as traditional approaches, if it is possible in the same amount of time and in only one stroke. . . The available empirical data on learning scientific conceptions demand more radical changes" (p. 280).

> Educational technology can serve as a useful tool in the development of complex skills – but not in isolation. Successful teaching of complex skills greatly depends on an instructional plan that carefully considers what is to be learned, what the technology contributes, and what the learning environment and the teacher must provide. The instructional plan must ensure that students receive ongoing guidance—guidance that often comes from the teacher but that may come from instructional materials or other students as well. Student collaboration is often an important aspect of the learning process. Teachers are called upon to play a variety of roles; to be a learning environment manager as well as an information provider (Sivin-Kachala & Bialo, 1995, p. 3).

The need for in-depth understandings of both pedagogy, subject matter, and skills in using technology

Instruction that is based in constructivist principles is extremely demanding of the teacher. Borko and Putnam (1995) identify three domains of teacher knowledge that are important to their effectiveness in moving to constructivist approaches: "general pedagogical knowledge, subject-matter knowledge, and pedagogical content knowledge" (p. 38). They also cite Ball's (1990) work in mathematics education. She

> argues that to teach mathematics for understanding, teachers' knowledge of mathematics must meet three criteria: (1) teachers' knowledge of concepts and procedures must be correct, (2) teachers must understand the principles and meanings that underlie mathematical procedures, and (3) they must appreciate and understand the connections among mathematical ideas. (pp. 43-44)

Yet there is strong evidence that, in mathematics and other subject areas as well, teachers are woefully under prepared. Neither current preservice education programs nor standard professional development practices offer teachers the experiences and tools they need for in-depth pedagogical and subject area understanding (Aichele & Coxford, 1994; Boethel, 1996; Borko & Putnam, 1995).

Technology adds yet another skill set that teachers must master. Past experience with assisting teachers to learn to use technology to support problem-based learning indicated that teachers were forced to choose between learning new ways of structuring the classroom or learning how to use technology (Dimock & Rood, 1996). As Sandholtz et al. (1997) point out, "The addition of technology can exacerbate or enhance the already complex challenge of teaching" (p. 183). Professional development and teacher preparation programs have not caught up with the needs of teachers in learning the skills necessary for using technology to support constructivist learning environments (Sandholtz et al. 1997).

Creating constructivist learning environments supported by technology

Virtual, electronic, and real-world elements together provide tools and resources for learners' construction of knowledge. The combination of constructivist learning environments with technology is complex and yet important when considering the press to prepare learners for the twenty-first century. Students live in an Information Age in which geographic mobility, intellectual flexibility, and the synthesis of work and learning are the norms in the workplace (Dolence & Norris, 1995). Educators have an opportunity to motivate students and help them develop critical thinking skills that will make them viable and contributing members of society in the next century.

Much remains to be learned about how to overcome the barriers cited above. The model proposed by Means et al. (1993) and recommendations for teachers who wish to create constructivist learning environments (see Brooks and Brooks, 1993) are informative. More investigation of these environments is needed, however, to verify the few research-based studies described here. Data that reflect the process of creating and implementing a constructivist learning environment should illustrate the many variations possible. Rather than reduce characteristics to a few abstract variables, descriptive studies could provide practitioners with valid and practical models through rich description of such environments. If technology is to achieve its potential for supporting constructivist learning environments, models of those environments and how technology can be used as a tool are needed.

Professional development about constructivist learning environments, technology, and the interplay between the two is needed as well. An essential component often missing from most technology implementation efforts is professional development that helps teachers "think about how technology can support one's own instructional goals and learn how to orchestrate a class in which students are doing challenging projects, portions of which are technology based" (Means et al. 1993, p. S-4).

Knowledge about what comprises effective professional development to achieve these aims is needed as well. Professional development is needed that allows teachers to construct professional knowledge about pedagogy, content, and technology, as well as strategies for managing the changing classroom environments brought about with the creation of constructivist learning environments supported by technology. Just as constructivist learning theory informs the transformation of classroom environments for students, it also informs the development of learning experiences for teachers. These experiences should be situated in an authentic context for teachers, their school and classrooms. It should build on their prior knowledge and provide opportunities for social interaction with colleagues. It should begin with investigation of problems supported by technology that are relevant to teachers. By providing the very experiences promoted for constructivist learning environments in the classroom, it is possible that teachers will confront their "theories in use" to enable them to create learning experiences appropriate for the children of the Information Age.

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