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CSCL: THEORY AND PRACTICE OF AN EMERGING PARADIGM

Edited by

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For my mother,
who was a teacher

CHAPTER

4

Computer-Supported Problem-Based Learning: A Principled Approach to the Use of Computers in Collaborative Learning

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A frequent charge leveled against technological innovations in education is that they often seem to be designed to exploit the capabilities of the technology rather than designed to meet an instructional need; that is, that they are technology-driven rather than theory-based. It is not totally clear, however, what constitutes a theory-based approach, especially because there are a variety of different types of theories that come into play—theories of how people learn, theories of how an instructional system should best be designed to accomplish these ends, theories of social interaction, theories of how people and technologies can best function together, and so forth. Most instructional innovations have at least some rudimentary underlying theory of learning and instruction, and most applications of technology in education operate from some theoretical notion of efficacy—even though it may not be made explicit by, or even be explicit for, the system designer. Clearly, just the existence of such a theory cannot serve as a sufficient condition for a useful theory-based approach.

In keeping with the theme of this book, we pose the question, How would one undertake a theory-based approach to the design of CSCL tools? We argue that such a project should progress through four steps: making explicit the instructional requirements that serve as design goals for the project; performing a detailed study of current educational practice with regard to these goals; developing a specification based on the identified requirements and limitations of the instructional setting, and the known capabilities of the technology; and producing an implementation that allows for local adaptation to instructional practice.

Design should be informed from its inception by some model of learning and instruction. Consequently, it is desirable that the designer be able to articulate these educational considerations from the earliest stages of the design. An educational model is important to the overall design, not only because it makes it possible to later evaluate the success of the innovation, but also because it provides a standard for evaluating the current instructional setting, revealing aspects of current practice that fall short of specified goals. The outcome of this analysis is a list of requirements for the innovation. A system specification is produced by matching these requirements with the known capabilities of the technology. The ultimate realization of the planned innovation occurs when the users (i.e., teachers and students) are able to incorporate it into practice in a way that will effectively serve their instructional requirements. The design, therefore, must be sufficiently flexible to allow these ultimate users to adapt the technology to best meet their needs.

In this chapter, we present a case study that demonstrates how this approach can be applied within a particular method of instruction and educational setting. The method chosen is a collaborative form of instruction known as problem-based learning (PBL). Although PBL is being utilized in a variety of educational settings and levels, we discuss its use in the context of medical education, a domain of study that is simultaneously complex and ill-structured. We begin by articulating what we view to be critical features of effective learning and instruction in such domains. After stating these commitments in the form of a list of principles, we analyze how well PBL meets these expectations in practice. We then propose several ways that the method can be made to better satisfy these instructional goals through the introduction of technology, the outcome being Computer-Supported Problem-Based Learning, an approach that preserves the educationally important features of PBL while at the same time enhancing it through the affordances of a technology-enriched environment.

The list of principles of effective learning and instruction is encountered four times in this chapter—once in exposition, once in evaluating the strengths and weaknesses of PBL as currently practiced, once to motivate the uses of technology in PBL, and one final time to reveal connections to other related methods of instruction. Although this may seem repetitive, we ask the reader's forbearance; it is simply an example of how complex concepts are made understandable by revisiting them multiple times in different contexts.

KNOWLEDGE, PRACTICES AND PRINCIPLES OF LEARNING AND INSTRUCTION

What Graduates Should Be (but Usually Aren't)

Education should produce individuals who have a sound working knowledge base, who can use that knowledge when called upon to do so, and who are willing and able to continue the learning process after schooling. There has been increasing concern about the ability of the American education system, elementary through postgraduate, to produce such individuals (GPEP, 1984; National Commission on Excellence in Education, 1983; National Science Foundation, 1982; Porter, 1989). Students at all levels demonstrate significant errors in their knowledge (e.g., Brown & Burton, 1978; Coulson, Feltovich, & Spiro, 1989; Perkins & Simmons, 1989); they do not remember what they have learned (e.g. Farr, 1987; Levine & Forman, 1973); and they cannot productively use what they do remember (e.g., Feltovich, Johnson, Moller, & Swanson, 1984; Wason & Johnson-Laird, 1972; Whitehead, 1929). Perhaps most significantly, they often do not know when they do not know; and when they are aware of their lack of knowledge, they do not know what to do about it (e.g., Bransford, Stein, Shelton, & Owings, 1981; Chi, Bassok, Lewis, Reimann, & Glaser, 1989). In short, existing educational systems are producing individuals who fail to develop a valid, robust knowledge base; who have difficulty reasoning with and applying knowledge; and who lack the ability to reflect upon their performance and continue the process of learning. There are a number of likely, intertwined causes for these failures of education.

Difficulties in Developing a Valid, Robust Knowledge Base: Problems of Complexity. Problems of validity of knowledge, or misconceptions, can be traced at least partly to the difficulty, and resultant oversimplification, of complex subject matter. In this regard, some important concepts have been found to be difficult for students to master and to apply for a variety of reasons (Dawson-Saunders, Feltovich, Coulson, & Steward, 1990; Feltovich, Spiro, & Coulson, 1989, 1993). Because of their elaborate and complex nature, understanding these concepts may make unusual demands on ordinary cognitive processes. They may operate in ways that run counter to everyday experience, making them seem counterintuitive. Moreover, many complex concepts do not stand alone; they interact and are co-defined in a complex fashion with many others, making their learning in isolation problematic.

Instructional attempts to simplify, interpret, or illustrate complex concepts using concrete representations may actually contribute to or reinforce erroneous understanding (Coulson et al., 1989; Feltovich et al., 1989, 1993; Myers, Feltovich, Coulson, Adami, & Spiro, 1990; Spiro, Feltovich, Coulson, & Anderson, 1989). Further, the selection of unnaturally simple and contrived (i.e., textbook) cases as examples and exercises contributes to the development of an oversimplified view of how complex concepts are applied in practice (Coulson et al., 1989; Feltovich et al., 1989).

Difficulties in developing a robust, well-retained knowledge base have been traced to a number of factors, as well, many of them also related to attempts to reduce both the interconnectedness and complexity of material (Farr, 1987). In knowledge development, robustness is a function of the number and nature of associations made and how often the knowledge is used. In education, this translates to the students encountering material from a number of perspectives with ample time for reflection on the interrelationship of these perspectives, as well as a number of opportunities for the application of the knowledge. Knowledge acquired through memorization of isolated facts and stored in isolated compartments is likely to be inaccessible in problem contexts and, if not used, may soon be lost completely (Spiro, Vispoel, Schmitz, Samarapungavan, & Boerger, 1987). Unfortunately, the general approach of those responsible for curriculum and instruction, when faced with the task of adding more and more essential material to the same amount of instructional time, is to condense richly interconnected concepts to easily remembered statements, formulas, outlines, or lists. The resulting curriculum, while possibly bolstering students' examination performance, works against the development of a robust knowledge base in at least three ways. First, the pace with which material must be covered does not allow for thinking, reflecting upon the material, and trying out the knowledge in a variety of ways—processes essential to developing a rich network of associations. Second, efforts to simplify, condense, and circumscribe material so that more can be covered in the same amount of time also make the concepts less amenable to association and connection (or more prone to compartmentalization). Third, it may be the case that the processes that faculty use to extract the essence of a topic (again in order to improve efficiency) are processes that themselves expand on and reinforce meaning and, hence, memorability. Unfortunately, when faculty do the extracting, these benefits accrue to them and not to the student.

Difficulties in Developing the Ability to Reason With and Apply Knowledge: Ill-Structured Problems in Ill-Structured Domains. Not only are some areas of knowledge complex and difficult, this knowledge may also be difficult to apply; that is, performance that calls upon the use of complex knowledge in ill-defined contexts may present particular difficulties. There are at least two reasons for this, both having to do with ill-structuredness. First, the domain of knowledge itself may be ill structured; second, the problems that challenge performance in that domain may be ill structured. The distinction is important.

Spiro and colleagues (Spiro, Coulson, Feltovich, & Anderson, 1988) have characterized an ill-structured knowledge domain as one in which no single concept, or even a small number of conceptual elements, is sufficient for capturing the workings of a typical instance of knowledge application (which we call a *case*). Further, the patterns of applicability between sets of concepts and cases to which they are pertinent are irregular. Put another way, many concepts will be necessary for understanding a case, and although a set of cases might nominally be classified as being the same type (e.g., all cases of hypertension), different groups of concepts may be applicable across instances of this class. The relationship between conceptual knowledge and the case is irregular. In addition to conceptual knowledge, knowledge representation in ill-structured domains may take the form of previously experienced cases that, along with conceptual knowledge, can be configured and reconfigured to accommodate variance as it emerges; but even these configuration patterns are irregular and amorphous.

Ill-structured problems, on the other hand, represent a special challenge to knowledge application in a domain. Barrows and Feltovich (1987) described ill-structured problems as having the following characteristics: Defining the problem requires more information than is initially available—the nature of the problem unfolds over time; there is no single, right way to get that information; as new information is obtained, the problem changes; decisions must be made in the absence of definitive knowledge; and there may never be certainty about having made the right decision (cf. Reitman, 1965; Simon, 1973). As the parameters of a problem become defined, a personalized representation of a case is built. This representation is added to the repertoire of cases that constitute part of the learner's working knowledge of the domain. This episodic knowledge is subject to the same reconfiguration and re-use in other performance situations as is conceptual knowledge in the domain.

Education aimed at developing competence in such a domain presents a special challenge. For example, because of the problem of multiclassifiability and the irregular patterns of features across cases of the same type (Feltovich, Coulson, Spiro, & Dawson-Saunders, 1992; Feltovich et al., 1984), classification of cases cannot be done in any simple, regular manner. Further, teaching conceptual knowledge in the abstract will not prepare the student for the concepts' variations and combinations with other concepts that practice will demand (Feltovich et al., 1992, 1993; Spiro et al., 1987, 1988). Finally, each problem that challenges performance is unique with respect to the definitive parameters that it lacks and the possibilities for their definition. It should be noted that the presence of ill-structured problems in ill-structured domains is probably typical of most substantive attempts to use knowledge effectively in the real world. Well-structured knowledge domains and well-structured problems are almost exclusively the property of schooling, posing a double jeopardy for students as they are led to believe that learning clearly defined concepts and then solving nice, neat problems is learning, while being denied the opportunity to wrestle with real-world complexity.

Difficulties in Developing the Ability to Reflect Upon and Continue the Learning Process. The development of life-long learners is an oft-touted, rarely achieved goal of almost every educational enterprise. The failure to achieve this goal is of widespread concern, especially in flourishing fields such as medicine, where knowledge and technology are rapidly expanding and changing (GPEP, 1984). Traditionally, efforts to produce life-long learners have been directed toward the development of specific skills in library or resource usage, coupled with lectures on the value of keeping up. Little is done systematically to shift the responsibility for learning from teacher to student, and to develop the cognitive disposition and competence to carry out that responsibility.

Six Principles of Effective Learning and Instruction

Research in education and cognitive science can provide some guidance for what is necessary for promoting effective instruction and for overcoming the difficulties just described in complex, ill-structured domains. The implications of this work can be summarized in the form of six principles, which are listed in Table 4.1 and described in greater detail later.[1] In subsequent sections, these principles will be used as a basis for analyzing a particular approach to instruction and as guidelines for proposing technological augmentations in the classroom. These principles therefore serve as an example of an attempt to articulate the design goals for an educational system, as discussed in the introduction.

Principle of Multiplicity: Knowledge Is Complex, Dynamic, Context-Sensitive, and Interactively Related; Instruction Should Promote Multiple Perspectives, Representations, and Strategies. Single mental representations, and methods of approach, are not likely to be sufficient for capturing the nature of complex materials of learning and of knowledge application in ill-structured domains. Aspects of richness in concepts and cases will be missed with single representations, and the resultant simplification may prove misleading (Spiro et al., 1989; Weller, 1970; Zook & DiVesta, 1991). Hence, the use of multiple perspectives and knowledge representations

[1]A somewhat different elaboration of Principles of Effective Instruction is given in Feltovich et al. (1993).

TABLE 4.1
Principles of Learning and Effective Instruction in Domains and Problems That Are Complex and Ill Structured

Principle of Multiplicity
Knowledge is complex, dynamic, context-sensitive, and interactively related; instruction should promote multiple perspectives, representations, and strategies.
Principle of Activeness
Learning is an active process, requiring mental construction on the part of the learner; instruction should foster cognitive initiative and effort after meaning.
Principle of Accommodation and Adaptation
Learning is a process of accommodation and adaptation; instruction should stimulate ongoing appraisal, incorporation and/or modification of the learner's understanding.
Principle of Authenticity
Learning is sensitive to perspective, goals, and context, that is, the learner's orientation, goals, and experiences in the learning process determine the nature and usability of what is learned; instruction, therefore, should provide for engagement in the types of activities that are required and valued in the real world.
Principle of Articulation
Learning is enhanced by articulation, abstraction, and commitment on the part of the learner; instruction should provide opportunities for learners to articulate their newly acquired knowledge.
Principle of Termlessness
Learning of rich material is termless; instruction should instill a sense of tentativeness with regard to knowing, a realization that understanding of complex material is never "completed," only enriched, and a life-long commitment to advancing one's knowledge.

should be encouraged in learning (e.g., Champagne, Gunstone, & Klopfer, 1985a; Feltovich et al., 1993; Lesgold & Katz, 1992; Spiro et al., 1989). Central to the idea of multiple perspectives and representations is the revisiting of concepts and cases as knowledge matures and is enriched (e.g., Norman, 1977; Spiro, Feltovich, Jacobson, & Coulson, 1991a, 1991b).

Principle of Activeness: Learning Is an Active Process, Requiring Mental Construction on the Part of the Learner; Instruction Should Foster Cognitive Initiative and Effort After Meaning. Learning is not a passive process of reception, but, rather, a constructive process of knowledge assembly, influenced greatly by what is already known (Bartlett, 1932; Bransford & Franks, 1972; Gates, 1917; King, 1992; Spiro, 1980; Tulving & Thomson, 1973). It has also been shown that one can discriminate between good and poor learners on the basis of the activeness and self-initiative by which they pursue learning (Bransford et al., 1982; Chi & Bassok, 1989). This principle applies whether the learner's goal is to build a valid, robust, usable knowledge base or to memorize a list in order to pass a test (e.g., Spiro, 1980; Tulving, 1962). Active mental construction must be carried out in either case; it is the focus of the effort that differs. Researchers (e.g., Scardamalia & Bereiter, 1989, 1991) have emphasized the importance of one specific kind of effort, the learner's intentions, with respect to acquiring knowledge and the importance of developing in the learner an independent agency for learning. The effective learner is driven by a need to know and is able to identify what needs to be learned in light of the context.

Activeness on the part of the learner may also be viewed from the perspective of the uses to which knowledge is put. As discussed earlier, real-world problems are ill structured. Often they require more information than is initially available; they change as new information emerges; and action must be taken in the absence of complete information and with less than full certainty of correctness. Real-world problem solving, then, demands activeness in the form of aggressive inquiry, reasoning, and reflecting. An effective instructional method should promote activeness in learning through self-direction, goal setting, problem finding, problem solving, and self-testing, and should engage the learner in problem solving that requires the aggressive inquiry, reasoning, and reflecting demanded of ill-structured problems and knowledge domains.

Principle of Accommodation and Adaptation: Learning Is a Process of Accommodation and Adaptation; Instruction Should Stimulate Ongoing Appraisal, Incorporation and/or Modification of the Learner's Understanding. What one understands and subsequently remembers about any educational experience, whether text-based or direct experience, is a function of the learner's previously existing knowledge and beliefs with respect to that experience (e.g., Chiesi, Spilich, & Voss, 1979). The outcome of any learning experience, then, is a function of the mutual adaptation of learner to experience and experience to learner. This has three implications for instruction: Instruction should take advantage of the learner's prior understanding as a rich foundation on which to build; it should allow for ongoing monitoring of the learner's understanding in order to make midcourse corrections and to challenge erroneous ideas (McKendree, 1990); and it should promote the development of cognitive flexibility so that appropriate adaptation occurs (Spiro et al., 1991a, 1991b).

Students bring to any educational setting a rich background of knowledge and experience on which to build. It is often a surprise to educators to find that when students are allowed to fully engage in a learning experience, as opposed to being constrained by an academic ritual, they exhibit a surprising amount of relevant knowledge of which neither the student nor instructor may have been aware (cf. Barrows & Tamblyn, 1980). On the other hand, the background knowledge and preliminary understandings students bring to an instructional exercise may be deficient or faulty. Further, their reconstruction of the subject matter learned may be inaccurate for a variety of reasons (Coulson et al., 1989; Feltovich et al., 1989; Myers et al., 1990). Faulty or impoverished prior knowledge can perpetuate itself in new learning (e.g., Anderson & Pichert, 1978; Chiesi et al., 1979; Feltovich et al., 1989). Such considerations present problems for learning that can only be remedied by adapting instruction to fit the students' needs and backgrounds. Instruction must, therefore, be flexible. Skilled instructors are constantly assessing the understanding of their students to detect deficiencies, to repair (or lead the student to repair) misconceptions, and to encourage deeper exploration of complex topics students may feel they already know (Collins & Stevens, 1982). Such instructional behavior serves as a model for the kind of self-questioning from which essential metacognitive skills of learning develop.

Finally, the flexibility that adaptation occurs with may vary widely from learner to learner. Some exercise a very rigid approach to learning experiences; their perception is highly constrained by what they already believe to be true, and incoming information and/or later reconstruction is highly filtered and altered by preexisting beliefs. Other learners may have a more highly developed ability to take multiple perspectives with respect to a learning experience (in a sense, a greater ability to argue constructively with themselves and others—Cavalli-Sforza, Lesgold, & Weiner, 1992), as well as the capacity to shape the experience itself in order to make it more amenable to adaptation (processes of cognitive flexibility—e.g., Spiro et al., 1988).

In summary, instruction should facilitate adaptability in all these respects: It should build upon preexisting foundations, monitor for and encourage correction when misconceptions are identified, and foster the development of cognitive flexibility so that the learner's efforts toward learning have the greatest possible effect.

Principle of Authenticity: Learning Is Sensitive to Perspective, Goals, and Context, That Is, the Learner's Orientation, Goals, and Experiences in the Learning Process Determine the Nature and Usability of What Is Learned; Instruction, Therefore, Should Provide for Engagement in the Types of Activities That Are Required and Valued in the Real World. Learning is sensitive to perspective, goal, and context (e.g., Anderson & Pichert, 1978; Brown, Collins, & Duguid, 1989; Jenkins, 1969). The context in which learning occurs, including the goals for learning that exist at the time of acquisition and the related perspective adopted with regard to materials of learning, can affect the learner's ability to retrieve and apply the knowledge subsequently (e.g., Tulving & Thomson, 1973). The potential usefulness of knowledge is a function of the congruency between conditions of knowledge acquisition and the conditions of knowledge application (Baddeley, 1982; Tulving & Thomson, 1973). Among other things, this suggests that the learning of basic conceptual knowledge should not be separated from applications of this knowledge as it often is; but rather, to be useful, knowledge acquisition and application should be highly intertwined (Bransford, Vye, Kinzer, & Risko, 1990; Glaser, 1984).

The irregular patterns of applicability of conceptual knowledge to cases of application in ill-structured knowledge domains, and the irregular ways that ill-structured problems unfold over time accentuate the need to study particular instances within such a field and to engage in the practice of problem solving. There is too much context-sensitive variability in application of conceptual knowledge to be able to focus effectively only on knowledge in the abstract (e.g., Feltovich et al., 1993; Spiro et al., 1991a). There is too much variability in the dynamic unfolding of cases themselves to be able to prescribe any universal method for investigating and building a case. These characteristics provide some of the rationale behind case-centered instruction[2] (Bransford, Sherwood, Hasselbring, Kinzer, & Williams, 1990) and for using inquiry-oriented problems, that is, problems that require the student to interrogate and build the problem context, in such instruction (Barrows, 1990). The use of cases in instruction allows for conveying patterns of irregular application of knowledge, and for establishing rich sets of connections among concepts and between sets of concepts and cases to which they are relevant. It fosters the ability to assemble knowledge flexibly to suit the needs of particular instances of application (e.g., Spiro et al., 1988; Spiro & Jehng, 1990), rather than the ability to retrieve broadly scoped, preassembled structures of knowledge (i.e., schemas) that are only applicable in well-structured, routine situations (Spiro, 1977). Working with inquiry-oriented problems emphasizes the importance of learning how to interrogate and build a case interpretation.

More generally, students should be called upon to engage in the same activities in their learning that they will be called upon to perform in eventual practice (Lave, 1988).[3] Instruction, therefore, should be organized around real world problems in order to induce orientations to learning that

[2]Throughout this chapter, the term *case-centered instruction* is used generically to represent the class of methods in which teaching is primarily devoted to the study of a set of authentic problems or cases. Examples of such methods include Problem-Based (Barrows, 1994; Barrows & Tamblyn, 1980) and Project-Based Learning (Blumenfeld et al., 1991), Case Method Teaching (Williams, 1992), and Group Investigation (Sharan & Sharan, 1992). Specifically excluded would be any curricular model that is organized around discipline subject matter, delivering abstracted concepts or modes, with cases merely used as exemplars.

[3]The distinction between contexts of learning and practice is a deceptive one, however, because (as is discussed under the Principle of Termlessness) learning is a continuous and essential component of all practice.

are congruent with subsequent knowledge use, a central theme of theories of situated cognition (cf. Lave & Wenger, 1991) and a fundamental principle of problem-based learning (Barrows, 1994; Barrows & Tamblyn, 1980). In addition, learners should be encouraged early to appreciate the full richness and complexity of the problems of practice, including their ill-structured nature (cf. Barrows & Feltovich, 1987, regarding ill-structured problems; Feltovich et al., 1993; Spiro et al., 1988, regarding ill-structured knowledge domains). This will ward off overly simplistic orientations to learning and understanding that sometimes arise in learning encounters with difficult material (especially if the material itself is artificially simplified in instruction) and encourage cognitive adaptations to this complexity (e.g., Dember, 1991; Feltovich et al., 1989; Spiro et al., 1989). Lastly, the learner should be spared from engaging in activities that are only meaningful in an instructional context (i.e., *schoolwork* in its most pejorative sense) and that are wholly disconnected from the concerns of the real world (Lave, 1988).

Principle of Articulation: Learning Is Enhanced by Articulation, Abstraction, and Commitment on the Part of the Learner; Instruction Should Provide Opportunities for Learners to Articulate Their Newly Acquired Knowledge. We use the term *articulation* in a sense that combines two dimensions of its definition, "the act of giving utterance" and "the action or manner of jointing or interrelating" (*Webster's Ninth New Collegiate Dictionary*, 1985). Both dimensions unite in the service of pedagogical utility. Articulation as used here denotes giving utterance to force a cohesive explanation and interrelating of concepts and relationships. As a pedagogical activity, articulation can take a variety of forms, including generative summarization and the production of analogies (Wittrock & Alesandrini, 1990), predicting outcomes of events on the basis of current understanding (Champagne, Gunstone, & Klopfer, 1985b; White, 1984), and developing implicated questions about the learned material (King, 1992). Such activity serves a number of useful functions: It enhances retention (King, 1992), it illuminates the coherence of current understanding, it sensitizes knowledge points for impact by subsequent feedback (e.g., predicting an event makes the subsequent observation of results more powerful), and it forces the learner to take a stand on his or her knowledge in the presence of peers, making a commitment that calls for assessing and evaluating that knowledge and setting the stage for future learning.

Articulation serves another important function: It provides a mechanism for abstracting knowledge from the context in which it was acquired, thus increasing its utility. Learning in an environment that replicates the conceptual and contextual richness of the real world fosters in the learner an appreciation for that richness, but the effects of such learning are often opaque and tacit (Polanyi, 1967). The learner does not as a matter of course abstract principles from learning experiences; some additional cognitive effort appears to be essential (e.g., Larkin, 1989; Spiro et al., 1991a, 1991b; Szekely, 1950). Abstraction is especially difficult, context-sensitive, and limited in scope in ill-structured domains (Feltovich et al., 1992, 1993), but the processes involved may themselves be useful. In order to abstract principles from the various contexts in which they are embedded, the learner must view the cases from various perspectives, assembling and reassembling, to establish relationships and sort out which elements are generalizable and which are context specific. This cognitive effort provides practice in cognitive flexibility (Spiro et al., 1988). Articulating constructs and relationships forces the effort, with the added bonus of subjecting the outcome to observation and critique.

Principle of Termlessness: Learning of Rich Material Is Termless; Instruction Should Instill a Sense of Tentativeness With Regard to Knowing, a Realization That Understanding of Complex Material Is Never Completed, Only Enriched, and a Lifelong Commitment to Advancing One's Knowledge.[4] One of the characteristics of knowledge in complex domains is that it is multifaceted, open-ended, densely connected, ever changing, and context sensitive; consequently, learning in complex domains cannot be thought of as a closed system with a definable end point. If complex knowledge is approached appropriately, one does not learn, one is learning. Because knowledge changes meaning with context, values, perspectives, and new learning, learning must be dynamic and active to accommodate these changes. Instruction, then, should promote the development of a disposition toward and competence in initiating, reflecting on, and directing learning in response to the dynamics of the domain.

If schooling is to produce self-directed learners, tasks required in school learning should foster the capabilities that are essential for learning after formal schooling is complete (Myers, 1990). This includes fostering the development of metacognitive criteria for knowing when one knows and does not know, the ability to assess what needs to be learned in a particular problem context, the ability to identify and use resources efficiently to improve the state of one's knowledge, and the ability to reflect upon this process to improve its efficiency and effectiveness.

This principle raises a necessary tension: Complexity demands tentativeness; action demands confidence. The learner must be prepared to reconsider the validity of his or her knowledge as additional information or experience is acquired, and as context, perspective, and values change. Yet action demands a level of certainty sufficient to inspire confidence in the outcome of the action. The learner, therefore, must develop a skeptical certainty with respect to his or her knowledge base. This skeptical certainty is enhanced as learners are exposed to a variety of perspectives and opinions, both expert and nonexpert.

[4]Our choice of name for this principle was deliberate. The dictionary defines *termless* as "having no term or end, boundless" (*Webster's Ninth New Collegiate Dictionary*, 1985), which precisely captures the idea we were struggling to set forth. Also, the base word *term* has special meaning in the school context (i.e., "division in a school year during which instruction is regularly given to students"). *Termlessness*, then, implies that completing a term or two of instruction is not sufficient to master complex material.

The next section instantiates the foregoing general discussion by considering education in a specific area, that of first and second year medical education. For reasons that will be described, instruction at this level is particularly difficult. Problem-based learning is one approach to reforming the first 2 years of medical education. We describe in some detail the nature of this approach to instruction and evaluate it in the light of the six principles of effective learning and instruction just described. Finally, we show how technology can be used to augment this method, thereby enabling it to better meet the instructional goals underlying the principles.

PROBLEM-BASED LEARNING: A COLLABORATIVE METHOD FOR PRECLINICAL MEDICAL EDUCATION

Problems of Traditional Preclinical Education

Medicine is extraordinarily complex because of the nature of pertinent knowledge and the kinds of problems that are encountered (Schafner, 1989). It is a prime example of a domain that is both complex and ill structured, both in its knowledge and in its application of knowledge in practice. The application of basic science conceptual knowledge in medicine is especially difficult both because biomedical knowledge and its relations to instances of application are ill structured (Feltovich et al., 1992), and because patient problems themselves are ill structured (Barrows & Feltovich, 1987). Hence, the fields of medicine and medical education are vulnerable to the problems of education that we have discussed as being associated with such realms.[5]

The undergraduate training of a physician typically requires four years of instruction post-baccalaureate. Traditionally these 4 years are divided into 2 years of preclinical, basic science education, followed by 1 year of rotating clinical clerkships, and 1 year devoted to electives. The preclinical years are critical, because this is the period in which the medical student is exposed to much of the theory underlying medical science, presumably providing a foundation for later training and eventual practice. The amount

[5]As attested to by the fact that many of the references used as support for deficiency in learning in ill-structured domains cited earlier in this chapter were from the field of medicine (e.g., Feltovich et al., 1989; Levine & Forman, 1973).

of information that must be acquired by students during this period is immense (Pauker, Gorry, Kassirer, & Schwartz, 1976) and continues to grow at a rapid rate, leading to behavior in learning and instruction that may actually interfere with the achievement of the fundamental goals of education outlined earlier (Feltovich et al., 1989, 1993; Spiro et al., 1989), inhibiting the development of a sound, robust knowledge base; the ability to reason with and apply this knowledge in problem contexts; and the ability to reflect upon and advance the learning process.

The most prevalent mode of instruction in the preclinical years has involved teaching through lecture and laboratory experiences; there is generally little integration of instruction across disciplines and very little, if any, contact with clinical patient problems. Under this system, one that separates classroom learning from the application of knowledge, there has been a longstanding concern about the amount and quality of basic knowledge retained by students for use in clinical training (e.g., Levine & Forman, 1973), and a growing concern about the accuracy of the knowledge (e.g., Coulson et al., 1989). There are also questions about students' abilities to apply this knowledge to clinical cases (e.g., Lesgold et al., 1988; Myers et al., 1990; Patel, Kaufman, & Magder, 1991).

In summary, educating competent physicians is difficult. The amount of material that must be learned is vast, and it is conceptually complex. Patient problems are ill structured; information about the problem must be uncovered, dynamically changing the problem as it emerges, and decisions must be made and action taken in the absence of complete information. Finally, medical knowledge and techniques for acquiring patient information are changing at a phenomenal rate, but little is done in traditional medical education to develop the cognitive disposition and competence necessary for the student to become an effective lifelong learner.

Overview of Problem-Based Learning

Problem-Based Learning (PBL) is a curricular reform that was first introduced with the founding of the Faculty of the Health Sciences at McMaster University in the late 1960s (Spaulding, 1969). It was implemented in response to student disenchantment with instruction in the preclinical (i.e., initial 2) years of medical school, which the students found inherently less exciting and rewarding than their later clinical experiences in clerkships and residencies. PBL has subsequently been adopted as a means of addressing some of the documented (cf. GPEP, 1984) problems of traditional approaches to medical education (ACME-TRI, 1993).

More generally, PBL can be considered an example of a collaborative, case-centered, and learner-directed method of instruction. It is now widely used, not only in medical education, but also in architecture (Donaldson, 1989; Maitland, 1991), biochemistry (Smith, Powell, & Wood, 1995), business administration (Merchant, 1995; Stinson & Milter, 1995), dentistry (Tedesco, 1990), economics (Garland, 1995), engineering (Cawley, 1989; Hmelo et al., 1995), geology (Smith & Hoersch, 1995), law (Kurtz, Wylie, & Gold, 1990; Moskovitz, 1992; Winsor, 1991), nursing (Higgins, 1994), optometry (Lovie-Kitchin, 1991), social work (Heycox & Bolzan, 1991), veterinary medicine (Edmundson, 1994), and other areas of postsecondary education (Boud, 1985). There are several current initiatives to introduce PBL into secondary and elementary education.

In medical education, PBL replaces the traditional discipline-oriented preclinical years with a curriculum in which basic biomedical sciences are learned in conjunction with and in order to understand clinical, medical cases (Barrows, 1994; Barrows & Tamblyn, 1980). In its ideal implementations, a small team of students (five or six is considered optimal), together with a PBL tutor/coach,[6] learn in the process of working through a collection of clinical teaching cases. The case takes the form of an ill-structured problem (Barrows, 1986), requiring students to develop the case from minimal presenting information. Because of practical considerations, it is usually necessary to simulate the encounter with the patient, rather than have the students interact with the actual patient in the clinic. Patient encounters can be simulated in a number of ways. Trained patient surrogates, known as standardized patients (Barrows, 1987), can be used for some cases. For others, a paper-based simulation, the problem-based learning module, is designed to allow for free inquiry, providing responses for any question, examination, or laboratory test an examiner might request for the actual patient (Distlehorst & Barrows, 1982).

The components of the actual process are shown in Fig. 4.1. This process was designed to replicate the reasoning process utilized by a skilled practitioner (Barrows & Feltovich, 1987). Data are gathered, hypotheses generated and tested, and conclusions drawn in an interactive, recursive manner similar to that used by the physician. Throughout the process, as students analyze the case, building a model of the patient's medical condition, they generate *learning issues*. These are areas of knowledge in which members of the group feel they are not sufficiently prepared for understanding the problem under study. These learning issues are usually focused on the basic science mechanisms that explain the clinical problem and its subsequent

[6]The faculty member participating in a PBL meeting is traditionally referred to as the *tutor*. This is an unfortunate choice of title, however, because it suggests a role that is largely at odds with the perceived function of that individual. Alternative titles such as "animateur" (Kurtz et al., 1990, p. 809), "facilitator or guide" (Barrows & Tamblyn, 1980, p. 83) have been proposed. We prefer the term *learning coach* or simply *coach*, which implies a somewhat different role for the group facilitator. Because the traditional terminology is so deeply entrenched, we refer to the faculty member in this chapter as the *tutor/coach*.

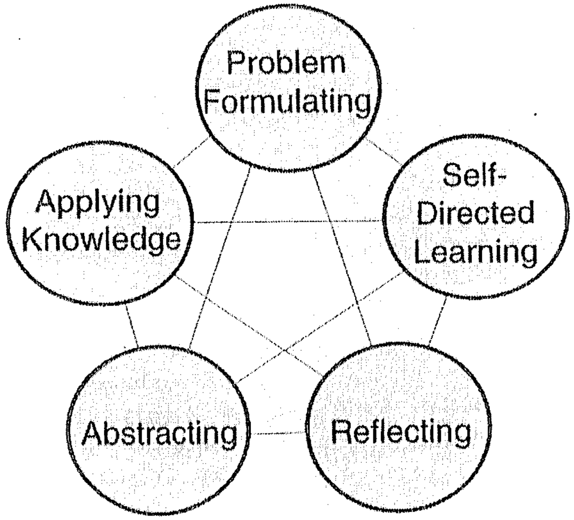

FIG. 4.1. Components of Problem-Based Learning.

management. Information and ideas as they develop within the group are organized and recorded on a whiteboard by a student assigned the role of scribe. The whiteboard is sectioned to hold information of specific types—emerging evidence with regard to the case (data), hypotheses of underlying cause (ideas), matters for further study (learning issues), and developing plans for future inquiry about the patient (actions). Students identify and utilize resources—person, print, and electronic—outside of the group that can provide the additional knowledge necessary for understanding and managing the patient's problem. At appropriate junctures, the group may also engage in abstracting and reflecting. When abstracting, the students are asked to articulate the knowledge they have acquired. The case is re-examined in the context of other cases the group has seen—to discern generalizations where possible, to make connections across lessons learned in different cases, and to explore similarities and differences. In phases of reflection, the group discusses their own approach to the problem, critiquing the learning process and identifying areas for future improvement. These components of the process do not occur in a pre-established order. Although one might be more likely to see problem formulating taking place early in the discussion of a case, and reflective activities toward its conclusion, the group may utilize any of these aspects of the process at any time. Rather than ritualistically honoring a fixed set of steps, therefore, there is an improvisational character to the method, making it responsive to the needs of the moment.

The PBL tutor/coach is an individual trained to facilitate this learning process. The coach's role includes monitoring group process and the participation of individuals within it, guiding the development of the clinical reasoning process by strategically questioning the rationale underlying the inquiry strategy of the group or individuals, externalizing self-questioning and self-reflection by directing appropriate questions to individuals or the group as a whole, and evaluating each student's development with respect to these criteria. A large part of the tutor/coach's role is to model and encourage the development of necessary metacognitive skills having to do with appraisal of the student's reasoning and understanding. Overriding this entire process, the tutor/coach must keep in mind that his involvement moves from modeling to coaching to fading (cf. Collins, Brown, & Newman, 1989) with respect to the various behaviors and understandings expected of students.

Although in a PBL curriculum the responsibility for learning resides with the students, there is a well-designed curricular infrastructure undergirding the process. Cases are developed from actual patient records and are presented in the way actual patients present themselves for care: as an ill-structured problem that must be built by inquiring to gather necessary information from history, physical examination, and laboratory data. Case selection for the curriculum involves a team approach, with basic science faculty providing from the perspective of their disciplines a list of critical topics about basic biomedical science mechanisms to be learned. Clinical faculty contribute insight as to the kinds of medical problems that are frequently encountered in practice and those that are less common but demand immediate diagnosis and treatment. Together the faculty work to balance basic science and clinical perspectives in arriving at a list of cases for possible use in the curriculum. As a part of the effort toward designing an authentic curriculum, PBL insists on ongoing, formative curriculum evaluation that allows for replacing or adding cases, dictated by the needs of students as they arise in group meetings.

PBL and the Six Principles of Effective Learning and Instruction

In the section that follows, the ways that PBL conforms to each of the six principles of instruction are discussed.[7] Despite embodying the principles in many ways, there are limitations imposed by both human capabilities and traditional tools of instruction that constrain the full potential of the method; these too are enumerated for each principle. This analysis provides an example of how the instructional requirements (in this case, the list of principles) can be used as a standard for evaluating current educational

[7]For an alternative treatment of the instructional theories underlying PBL, see Norman and Schmidt (1992).

practice and identifying opportunities for technological enhancement. In particular, these identified limitations motivate the design of the technological tools for enhancing PBL described later in this chapter.

PBL and the Principle of Multiplicity. The principle of multiplicity is realized through multiple representations, multiple encounters with concepts and cases, and multiple perspectives. Teaching cases can be studied from a rich variety of perspectives (e.g., basic mechanism of disease, diagnosis, anatomical structure and function, epidemiology, determination of patient prognosis), drawing upon all of the medically related disciplines. As shown in the diagram (Fig. 4.1), the process of analyzing the problem, identifying new issues for study, independently investigating these issues, and applying the acquired knowledge is reiterative. Following any period of self-directed learning, students return to the problem, reassessing their original formulation and motivated to seek additional information about the case in the form of questions to the patient, physical examination maneuvers, or laboratory tests. In the process, new (or refined) learning issues may again arise and the PBL process continues. The case is revisited until such a time that all members of the team feel that the vital aspects of the problem have been satisfactorily explored.

Furthermore, as a collaborative method, PBL encourages the development of multiple representations through exposure to the ideas of all members of the group. However, in contrast to the many benefits to be derived from group interaction (e.g., multiple points of view), there are some costs. Teaching methods that depend on group interaction often experience what is termed the *polling problem*; the opinions of individuals vary as a function of the order in which their views are gathered. Contributions of less dominant members may be suppressed or contaminated by the more dominant members, convictions of any single individual in the group may be inappropriately influenced by other members, individuals can find means to hide or ride on the coattails of other group members. The polling problem, therefore, can result in the suppression of ideas, reducing the multiplicity of viewpoints expressed.

PBL and the Principle of Activeness. PBL embodies the principle of activeness by placing the locus of control for learning with the student, and by presenting both cases and learning resources as grossly uninterpreted material. The student determines both the direction of inquiry about the case and the learning issues that are to be pursued. As a consequence, they must actively engage in the process, or be conspicuous by their lack of participation. The PBL method itself is designed to promote self-direction, goal setting, problem finding, problem solving, and self-testing—all elements of active, constructive learning.

However, there is a need for better record-keeping facilities within the group meeting. The sectioned whiteboard is inadequate in several regards. First, its limited space often leads to ideas being lost. Second, it is important to the development of the clinical reasoning process that students be able to compare their approach to a current case with approaches taken to previously studied cases. Because the board must be erased at the conclusion of a problem, the abstraction of principles across cases is limited by the ability of the members of the group to recall detailed features of previously studied cases. Finally, the notes on the board provide an incomplete record of the group's deliberations for the purposes of reflecting on the process.

PBL and the Principle of Accommodation and Adaptation. The PBL process provides for the unveiling of students' current knowledge and understanding, for uncovering misconceptions, and for forcing an awareness of the inadequacy of knowledge or incompetence in reasoning and self-directed learning, setting the stage for change—all essential to facilitating adaptation. The group process allows for the shared defining of meaning, allowing each individual the opportunity to take advantage of the struggles of other members to understand, thus facilitating his or her own adaptive processes. In the PBL process, the tutor/coach gains an awareness of the students' ongoing mental models through verbally challenging students' current understanding of the problem, asking them to defend their current theories, or to propose and justify the next step in planning toward a solution. The tutor/coach is able to monitor the students' understanding through open discussion and direct polling. All of this works to create an awareness, both for the coach and for the student, of both the depth and breadth at which the student understands and of misconceptions and deficits in knowledge and deficiencies in reasoning.

Ensuring that each student's constructions of fundamental concepts are valid can be difficult in educational methods that depend on self-directed learning, requiring ongoing monitoring and assessment.[8] The tutor/coach must not only deeply probe each student's comprehension—diagnosing misconceptions and knowledge deficiencies—but must also maintain accurate and dynamic models of each student's understanding. As the size of the group increases, coaches find that it becomes more and more difficult to stay in touch with all members of the group. Ongoing, formative assessment of individual performance within the group can be challenging for the tutor/coach. The solution to this problem again lies in developing better

[8]This is not to suggest that it is somehow easier in the more conventional classroom. On the contrary, without frequent opportunities for students to articulate their newly formed knowledge, it is undoubtedly even more difficult to avoid the development of misconceptions.

systems for monitoring and recording the contributions of individual members of the group.

PBL and the Principle of Authenticity. PBL realizes authenticity in several ways (Barrows, 1994). First, the curriculum is designed entirely around the study of cases developed from actual patient records. These are ill-structured cases in that they may include missing and erroneous data, unusual presentations, and so forth. Second, the student's process of inquiry is also authentic. Initially, only a small amount of information is provided to the students, requiring them to inquire for all the remaining information, as they would have to do in a real clinical encounter. Third, the components of the PBL process (see Fig. 4.1) represent aspects of actual clinical problem solving. Finally, even the investigation of learning issues is authentic, reflecting the way practicing physicians—often in response to problematic issues in the clinic—must keep up with current knowledge in their field through print and computer resources and the establishment of collegial relationships.

As mentioned earlier, PBL depends on simulating the encounter with the patient. All authentic simulations must address two issues. First, they must be of sufficient fidelity to preserve the educationally important features of the actual case. Second, the simulation must avoid inadvertently providing information that would not be available from a real patient, what we term the cueing problem. Cueing occurs when a description of a physical finding calls attention to details that might have been overlooked or interpreted differently by the student. For example a written finding of slurred speech would better be presented as a person speaking in a discernibly slurred way, rather than providing the student with the interpretation that the patient's speech is slurred.

Curriculum development is not limited to the development of individual cases. Careful consideration must be given to the selection of cases and the sequence in which they are introduced to the students. The development of a curricular plan is a complex problem, involving formulating a list of critical topics, seeking cases that can be used as vehicles for investigating these topics, and working to develop a core of cases that will guide students toward the knowledge and skills necessary for professional practice. Curriculum planners could use assistance to develop, maintain, and flexibly access a repertoire of carefully designed, realistic cases.

PBL and the Principle of Articulation. The Principle of Articulation involves both the act of paraphrasing newly acquired knowledge and the process of interrelating this knowledge to prior learning. PBL fosters articulation in the first sense through the course of the group's deliberations—participation in the PBL process dictates that students continuously put their ideas before the group. They are asked to commit themselves to hypotheses as to the patient's condition, plans for diagnosis and treatment,

and newly acquired knowledge, interrelating it with prior learning. Articulation, if it is to be of value, must be an expression of the thoughts, ideas, and conjectures of the individual and must reflect the level of commitment with which the individual holds them. If the benefits of articulation are to be insured for each student, there is a need to encourage the formulation and free expression of these ideas.

With respect to the second meaning of articulation, it is important that students integrate concepts as they move from one case to another. Recalling details of past cases can be difficult when the number of cases grows large. This poses problems for developing indexing systems for retrieving such knowledge. What is required in an ill-structured domain is the development of multiple indexing systems—indexing by case types, indexing by categories of abstracted knowledge, indexing by problem presentation, and so forth. The logistical problems of maintaining these multiple indexing systems unaided represent a potentially overwhelming challenge to individuals and groups.

PBL and the Principle of Termlessness. Students who engage in the PBL process with its inquiry, reasoning/problem-solving, and self-directed learning (often using original, uninterpreted literature) are bound to encounter a number of precepts central to the notion of Termlessness: Learning is lifelong; it is never over. Ideas and knowledge are constantly changing. Bright people (even "experts") disagree about important concepts and interpretations. Different perspectives (e.g., psychosocial versus molecular biological) emphasize different facets of a concept, but there is nevertheless a coherence to the concept; different contexts emphasize different facets of a concept, nevertheless, the concept maintains a certain integrity. Search for meaning is not a one-shot process; repeating the same search in service to a different goal yields different information and interpretations of existing information. There are some things that are not known but are nevertheless worth speculating about. These precepts are inherent in the PBL philosophy and encouraged in the method, and are certain to be discovered by the learner who actively and consistently engages in the self-directed investigation of learning issues. They also contribute in a powerful way to the development of skeptical certainty and the disposition toward lifelong learning. The very fact that learners identify and research their own learning issues lends a healthy tentativeness to their knowledge that is missing when encapsulated facts are handed down by a lecturer or textbook author who may serve as an authority figure.

PBL also fosters the development of the competencies necessary to be efficient and effective in lifelong learning. Through challenging on the part of tutor/coach and peers, students learn to critically reassess their assumptions and the legitimacy of their knowledge, developing a capability for recognizing deficiencies and errors in their understanding. They are guided in learning to formulate learning issues and they become skillful at seeking out and critiquing knowledge sources. They learn how to shape or reconstruct newly acquired knowledge so that it contributes to the solution of the clinical problem. Finally, they are guided toward learning to critique their own learning behavior and to improve upon its efficiency and effectiveness.

Again, although the method fosters these precepts and competencies, operationalizing them can be overwhelming. Multiple searches for understanding and the simultaneous consideration of multiple perspectives, instances, and contexts with respect to a concept require time, resources, and capacity. Anything that facilitates both access to resources and the capacity to manage, compare, and elaborate information and ideas would enhance the method.

The reader should recognize that this description of how PBL implements the six principles is somewhat oversimplified. The situation is made complex by the fact that the requirements overlap to some degree. For example, the need to promote the free expression of ideas in the group meetings certainly affects Multiplicity, but at the same time affects Articulation and Termlessness. Similarly, the need to organize and index information in the students' notes is an aspect of Articulation, but it is just as clearly related to the ability of the student to confront conceptual complexity over a multitude of cases (Principle of Multiplicity).

Augmenting PBL Through Technology

There have been a number of recent reports describing ways in which technology might be used to support PBL (Grissom & Koschmann, 1995; Hmelo et al., 1995; Mahling, Sorrows, & Skogseid, 1995; Stinson & Milter, 1995). Taken together they represent the beginnings of an emerging area of study within CSCL. The particular approach to Computer-Supported PBL described here is based on the requirements presented in the previous section, namely the need for an adequate collection of authentic cases with a mechanism for selecting appropriate cases from the collection, the need for a retrievable record of the group's deliberations for previously studied cases, the need for multiple viewpoints uncontaminated and uninhibited by group effects, the need for students to be able to share information outside of meetings, the need to readily access learning resources, and the need for students to be able to index their notes in a way that will facilitate later retrieval. What follows, therefore, is an attempt to enhance the outcomes of PBL through the judicious application of new technologies.

The Collaborative Learning Laboratory: Facilitation Through Shared Exchange. The centerpiece of this approach is a special facility for conducting PBL meetings, known as the Collaborative Learning Laboratory (CLL). The Colab facility constructed at Xerox Palo Alto Research Center (Stefik et al., 1987) provided the inspiration for the design of the CLL.

Facilities of this sort reflect a growing interest in the design of groupware (Stefik & Brown, 1989) and other technologies to support group work. The field of study known as Computer Support for Collaborative Work (CSCW) is founded on the notion that computers can be used to facilitate, augment, and even redefine social interactions among members of a working team (Greif, 1988; Galegher, Kraut, & Egido, 1990).

A conceptual view of the CLL is shown in Fig. 4.2. The participant workstations consist of a laptop computer (Macintosh Powerbook®) and a docking station. While working in the CLL, students can insert their Powerbook into a docking station, thereby joining the local-area network and enabling the use of a full-sized keyboard and a large color monitor. There is a large multiscan display viewable by all members of the group that can project the contents of any participant's screen (Ryan & Koschmann, 1994). The projection system can also be used to display video output from a variety of sources (e.g., videodisc, remote video cameras, video conferencing equipment). Each meeting participant, therefore, views two screens—one private and one shared. Because isolating meeting participants behind large CRTs would disrupt

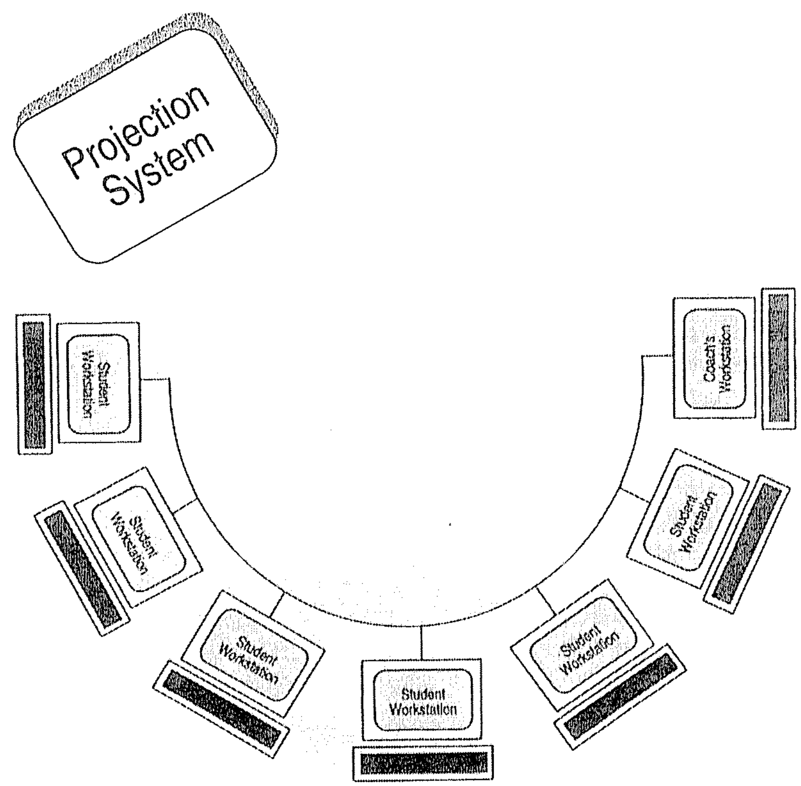

FIG. 4.2. Conceptual view of the Collaborative Learning Laboratory (CLL).

face-to-face interaction, specially designed desks are used to ensure that each member of the group has as an unrestricted view both of the shared screen and of the other members (see Fig. 4.3). The local-area network in the CLL is connected to the school-wide network, permitting meeting participants to access the electronic resources of the library and Internet.

Participants in the meeting may make use of a variety of programs—some developed specifically for this instructional setting, others off the shelf, commercial applications. Each workstation holds all of the usual software tools—for example, word processing programs, graphics programs, spreadsheets—that we have come to expect on personal computers. In addition to these standard applications, there is also a need for a general-purpose program to support interactive data sharing within the meetings. The e-talk program (Koschmann, 1993) was developed as a flexible platform for sharing data among the participants of a PBL meeting. It can best be described as a window-based chat system. Text typed on one workstation can be instantly displayed on the other participants' screens. The program supports two types of windows: a window in which to type messages (termed a *dispatch window*) and a window in which received dispatches are displayed (termed a *listener window*). Both dispatch and listener windows offer simple word processing capabilities, enabling the user to compose, dispatch, and annotate messages. Each user may have any number of each type of window. A variety of conference typologies can be constructed on top of these basic elements (Koschmann, 1993).

Meetings conducted in the CLL closely resemble PBL meetings unaugmented with technology—the valued forms of interaction and traditional group deliberation are preserved, but new resources are made available to support discussion and note taking. Several new instructional activities can be implemented using the facilities of the CLL (Koschmann, 1993). At various junctures, students working in the CLL will be asked to individually submit responses to open queries, a procedure we have termed *parallel polling*. The students respond by typing a message and sending it to the tutor/coach. Electronic polling of this type can be conducted in all components of the PBL process (e.g., problem formulating: "State and justify your leading diagnostic hypothesis for this case"; self-directed learning: "List likely resources for researching this learning issue"; applying knowledge: "Briefly summarize how yesterday's research can be applied to the current problem"; abstracting: "State the most important insight you have gained through the study of this case"; reflecting: "List three things that you could have done differently in studying this problem that would have led to better learning").

Electronic polling provides a private channel of communication in a public forum, enabling participants to express views uncontaminated by the opinions of others and leading to the display of multiple viewpoints (Principle of Multiplicity). Polling provides a snapshot of each student's understanding at specific points in the process, facilitating the coach's assessment of the

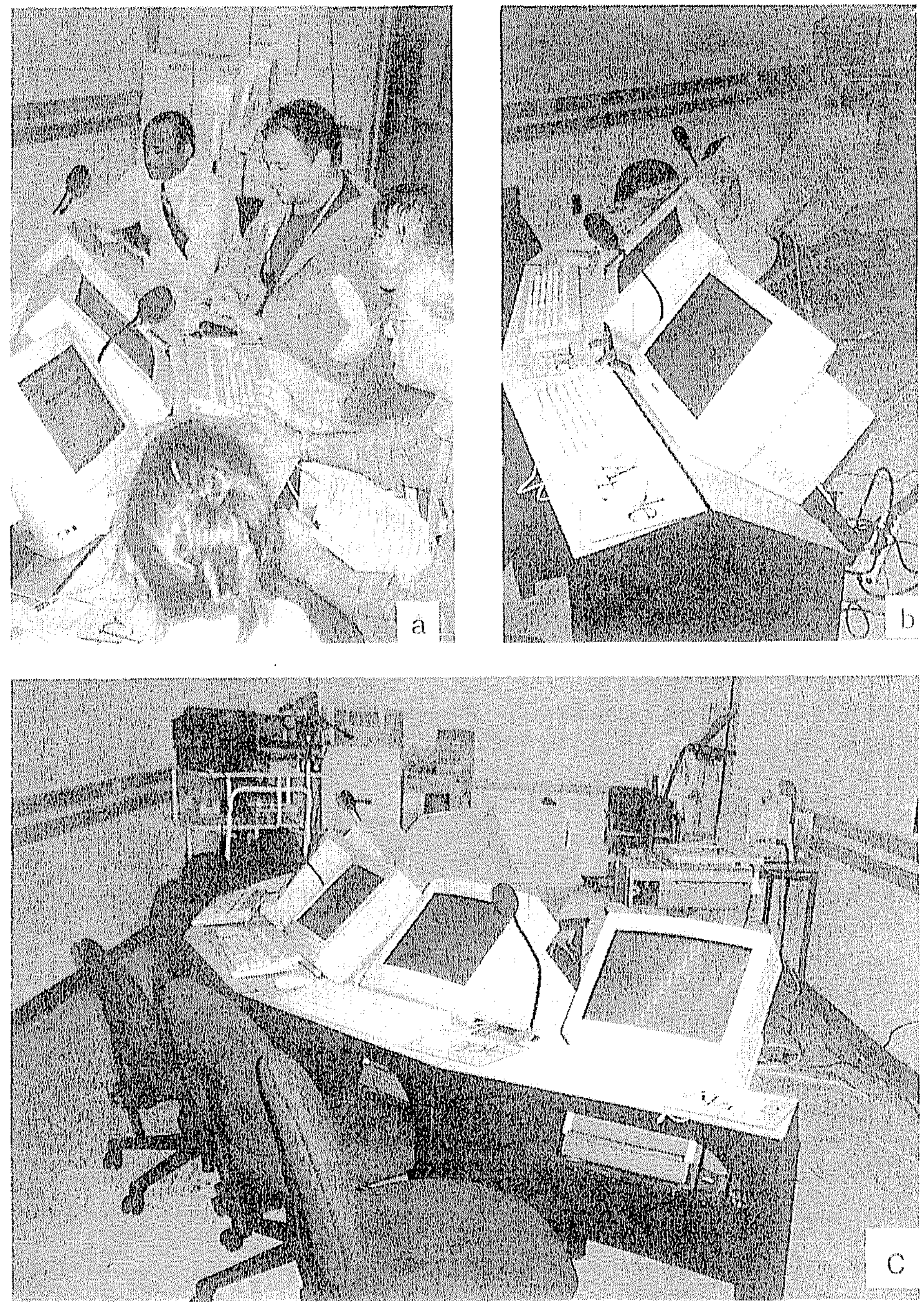

FIG. 4.3. A prototype of the Collaborative Learning Laboratory (CLL): (a) shows a PBL meeting being conducted in the CLL, (b) shows the specially designed desks, and (c) reveals one of the docking stations situated beneath the desk.

students' understanding. The CLL also provides for a permanent record of individual and group deliberation. This allows the tutor to review group process and plan for subsequent sessions, and to track the development of the educational goals over time for each individual within the group. Both reflect aspects of the Principle of Accommodation and Adaptation. At the discretion of the tutor/coach, the students' responses can be displayed on the projection screen or broadcast to the rest of the group (either anonymously or attributed). Exposing the individual responses to the scrutiny of the group can facilitate the clarification of individual points of view and lead to a more focused discussion of the issues (Principle of Activeness). Finally, by requiring students to resourcefully use informational technologies as a natural part of their curricular activities, they will at the same time acquire the information-gathering skills needed for later professional practice serving both Termlessness (Koschmann, 1995) and Authenticity. Given all these benefits, however, it should be recognized that computer-mediated communication is meant to augment group discussion, not replace it (see Conclusions).

Implementing the "Boards" as Distributed Hypertext: Facilitation Through Improved Access to the Representation of the Group's Deliberations on the Case. As discussed earlier, there are some problems with the record of the case constructed on the whiteboard by the group. First, because the capacity of the board is fixed, once it becomes filled something has to be erased in order to add anything new. Further, the contents of the board are invariably lost when the group takes up a new case, thus limiting the group's ability to contrast the current case with previously studied cases.

In the CLL, however, it is possible to create an electronic version of the boards that is accessible to all members of the group not only within but also outside of meetings. To be useful, the electronic representation of the boards should allow the group to impose some structure on the notes created and to be able to navigate easily amongst the elements of these notes; in other words, the representation should be *hypertextual*. Further, the notes should not be controlled by just one member of the group (as is the case when the scribe goes to the board), but should be accessible to (and updatable by) all participants in the meeting. The representation should, therefore, be implemented as a *distributed hypertext* with support for concurrent access by multiple users. Examples of distributed hypertext systems developed for use in education include: CSILE (Scardamalia et al., 1992), CaMILLE (Soloway, Guzdial, & Hay, 1994), and the CoVis Collaborative Notebook (Pea, 1993).

Implementing the boards as a distributed hypertext document affords several benefits to the process. Preserving a record of the group's deliberations makes it possible for the group to call up and revisit previously seen cases. This enables students to reevaluate the case in a variety of contexts, promoting the development of multiple perspectives (Principle of Multiplic-

ity). Further, by facilitating comparisons among cases, students are exposed to the interconnectedness of knowledge (Articulation in the second sense) and the fact that new learning is always possible (Principle of Termlessness). Because everyone can now write to the boards, the scribe's job becomes distributed across the group (i.e., one participant keeping track of Data, another of Ideas, and so forth). Such an approach enhances Activeness in two ways—all members of the group then become called upon to play some role in the "work" of the case while at the same time the scribe, with his or her responsibilities reduced, is able to participate more fully in the group problem solving. Finally, by making the board a document on the network, it can become an object of shared focus both within and outside of face-to-face meetings. It can serve, therefore, as a resource for the group's continuing dialogue about the case, again serving Articulation (in the first sense).

MMTs: Facilitation Through Realistic Case Presentations. Presentation of cases in the CLL will be done using a hypertext version of a PBLM, known as an MMT (Grissom & Koschmann, 1995). Textual data will be supplemented using videodisc or digitized video to present cases more vividly and with greater fidelity. As shown in Fig. 4.4, information pertaining to the case is divided into several related sections—patient interview, physical examination, and laboratory tests. The user can move from one section to another by

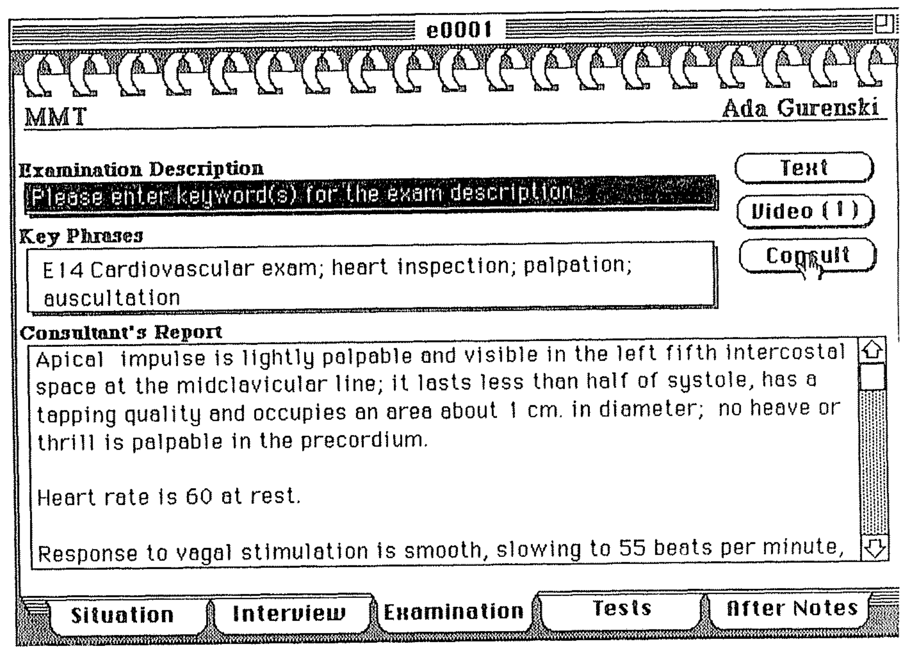

FIG. 4.4. A data screen from an MMT case presentation.

buttoning on the tabs that appear near the bottom of the data screen. The means by which students select individual items within a section of the MMT is designed to support an authentic process of inquiry (Barrows, 1990). Without menus or other forms of cueing, the students must generate their own list of pieces of clinical data to request. For any given data item, several types of resources may be available. Students access these resources through the buttons appearing on the right side of the data screen (see Fig. 4.4). Text resources provide a textual response similar to that found in the PBLM (Distlehorst & Barrows, 1982). Textual results are available as a default for all data items. Video resources are optional video segments for a particular item. Follow up resources are only provided for interview questions pertaining to patient symtomatology. They allow students to explore a finding in greater depth (e.g., When did *it* begin? What makes *it* worse? What makes *it* better?). A consult resource is a specialist's interpretation of a result. Consult resources are usually only provided for examination or test results. Normals resources consist of tables of normal laboratory result values and are only provided for test results. Cost-and-time resources provide an estimate of the cost to the patient and the amount of time required for particular test results.

The presentation of results as a set of resources was designed to create opportunities for group discussion (Principle of Articulation). For example, before looking at a result for a laboratory test, the group may consult the cost-and-time resource to determine whether or not this is the best way of obtaining a particular piece of information. After listening to a video clip of a cardiovascular exam, the group might attempt to formulate their own conclusions before opening the consult resource. Furthermore, MMT's are designed to address some of the previously described problems associated with Authenticity (i.e., fidelity and cueing). Through the use of video resources, MMT's can provide high-fidelity, uninterpreted representations of the clinical data.

Teaching Case Library (TCL): Facilitation Through Simplified Case and Curriculum Development. The production of teaching cases for the PBL curriculum is a laborious, time-consuming process. As the number of available teaching cases grows, locating appropriate cases for meeting specific curricular goals becomes a challenge for curriculum designers. Commercially available, relational database software has been used to create a repository for the case-related data used within the PBL curriculum.

We refer to this database of instructional materials as the Teaching Case Library (TCL). It has two important benefits. First, some of the stages of authoring and producing instructional materials (both MMT's and PBLMs) can now be automated (Grissom & Koschmann, 1995). This serves the Principle of Authenticity by making it possible to produce an adequate supply of authentic teaching cases. Second, the cases in the TCL can easily be indexed to permit their later retrieval by curriculum planners. Cases can

not only be indexed by surface features (e.g., diagnosis, presenting complaint, sex, and age of patient) but also by educationally relevant features, such as learning issues that are motivated by the problem or aspects of the problem that are likely to make it difficult for the students (Riesbeck & Schank, 1989). This enables the curriculum planners to more easily adapt the curriculum plan to meet the specific needs of the group and its individual members (Principle of Accommodation and Adaptation).

Electronic Case Notebook: Facilitation Through Retrieval of Case-Linked Material. Difficulties in retrieving particular kinds of cases and case-related material on demand are not limited to the curriculum planners. Students also encounter difficulties structuring their notes to facilitate later useful retrieval. Note taking is an important component of clinical practice; students are encouraged to maintain complete and accurate notes. Computers can assist in this task by creating a more readable representation (typed vs. hand-written), streamlining the process (cut and paste vs. typing) and by producing a searchable record. Information about the case under study (from the MMT) will be delivered to the students in the CLL electronically and portions extracted by students can be inserted directly into their personal notes. Although this has yet to be implemented, software is being planned to allow students to create an Electronic Case Notebook (ECN) of case-related material gathered during the PBL curriculum and later in their training.

The availability of the ECN serves the Principle of Articulation in both of its meanings. By providing the students a medium for recording their notes, it supports the expression of newly acquired knowledge. The ECN also will support the "jointing or interrelating" of cases and concepts by enabling the students to record linkages among cases. By providing a mechanism for indexing and retrieving case-related information, the ECN will satisfy the need for multiple indexing systems. Finally, the ECN will serve the Principle of Multiplicity by allowing the students to readily study a concept in its various guises as it applies to multiple cases.

Electronic Mail and Database Access: Facilitation Through Simplified Access to Resources. Two other, off-the-shelf forms of technical support will also be integrated into the curriculum. Electronic mail facilities will be used to facilitate communication outside of the group meeting, and computerized literature retrieval will enable students to locate quickly relevant resources from libraries.

Much of what makes PBL difficult can be viewed as a problem of communication. Because the process involves substantial independent research on the part of the students, opportunities for students to share information are limited outside of the scheduled group meetings. Also, resource faculty, consulted for help in understanding a problem, may not always be available at those opportune moments when students most need information. A simple remedy for these problems, however, is to install an electronic mail system to be used by both faculty and students. Students will have access to their e-mail accounts both within the CLL and between meetings, allowing them to extract information from their mail and share it with the group or insert it in their notes (Principles of Multiplicity and Activeness). With access to the Internet, students will be able to seek information from sources outside the school, providing a "window" to the world of professional practice and consultation (Principle of Authenticity).

For students in the PBL curriculum, each learning issue constitutes a small research project—resources must be identified, located and perused. Finding information in the primary literature is much more difficult than simply following a course outline in a text. Automating literature retrieval makes it feasible, if still not easy, to locate materials efficiently. Citations and abstracts for recent publications in the medical sciences can be made accessible through computer searches. Also, the catalog of the medical school library can be perused electronically to check for holdings and to determine the circulation status of instructional materials. Making learning resources readily available to students within the group supports the Principle of Activeness. The easy and broad access to many sources of alternative interpretation and opinion can contribute to an orientation to learning and knowledge that views these as neither fixed nor ever completed (Principles of Multiplicity and Termlessness). In PBL without technological support, the search for resources during the self-directed learning occurs outside of the meeting. Although the products of this search may later be discussed and critiqued during problem reexamination, the search process itself is not observable to the group. The library's electronic facilities for searching the periodic literature and current holding stacks will be accessible from within the CLL. This could enable one student to demonstrate information retrieval procedures using the projected screen, while the rest of the group observes. Activities of this kind stimulate valuable discussion about the usefulness of available learning materials, as well as facilitating the development of information retrieval skills (Principle of Termlessness).

DISCUSSION AND CONCLUSIONS

Why Computer-Talk Can't Replace People-Talk

Although we believe a strong case can be made for the use of computer-augmented interaction in the classroom, the reader should recognize that it would be undesirable to use it as the sole means of communication. Consideration of ideas has two phases: idea generation and group deliberation. Just as in "nominal group technique," a method that emerged from research into the facilitation of group process (Hill, 1982), electronic polling first forces the students to confront an issue and commit themselves as individuals. The results of the polling can then be presented to the whole group as a basis for initiating discussion. We believe that the deliberative phase is best conducted as before—through spoken discourse. Typed communication can be frustratingly slow. Also, although computer-mediated communication offers a "private channel of communication," it is a narrow channel—spoken discourse provides many cues (e.g., tonal, gestural) that are not carried in a typed message (Chapanis, 1988). Some forms of knowledge acquisition, therefore, are best left to free-wheeling interpersonal interactions where the comparison processes, dialectic, organization, and joint effort after meaning can transpire most naturally (e.g., Lesgold & Katz, 1992; Pea, chapter 7, this volume). Experienced educators must exercise some judgment in identifying times and places where computer-mediation can facilitate the process and where it might interfere.

A related point involves the inherent danger of introducing seductive electronic technologies of this sort into a classroom. Computers and video displays can serve as a powerful distraction, luring participants from the real task at hand. Kay (1991) described the captivating qualities of computer displays and how this can sometimes interfere with other activities in the classroom. The solution to the problem described by Kay is to carefully engineer the facility to minimize the distraction. For example, computer monitors can be sunk into the desk tops so that they do not obstruct the lines of sight among classroom participants (Cornell, Luchetti, Mack, & Olson, 1989). The computer desks used in our prototypic implementation of the CLL (see Fig. 4.3) have been carefully engineered to provide unobstructed views of all other members of the group.

It may appear to the reader that what we have proposed as tools to aid group learning are really vehicles for capturing individual contribution and learning, despite a group setting. This is to some extent true. There are circumstances in which the open group aids learning; for example, in the debate and dialectic over ideas and interpretations (Cavalli-Sforza et al., 1992; Pea, chapter 7, this volume); there are also times when evaluation and probing of individuals is important—even though they are working in a group (e.g., formal assessment). Nonetheless, it is easy to imagine that some of the tools we have proposed will also aid and enrich the group processes. For example, a richer and less attenuated set of ideas provided by the private channel should contribute to the process of debate. The tools that have been proposed enable instruction, when beneficial, to take advantage of the best of both group and individual learning.

Implications for Other Forms of Instruction

The six principles enumerated in the analysis were discussed in the context of preclinical medical education; not coincidentally, however, these principles are reflected by and are consonant with many other currently prominent approaches to instruction. The reasons for this are twofold. First, the principles themselves are based on basic research in cognition and instruction, enhancing their generality. Second, medical practice is not the sole example of a complex and ill-structured domain; indeed, most domains of real practice can be seen to show these characteristics to some degree. Therefore, although medical education has some special features, it is an educational undertaking that shares many characteristics with instruction at all levels—elementary through post-secondary. In fact, preclinical medical education is an interesting example for study because of the extreme demands that it places on the educational process. To see how the described work generalizes to other forms of education, we first outline the relationship of the six principles to three categories of currently prominent approaches to instruction, namely collaborative, case-centered, and learner-directed methods.

Learning in Groups: Collaborative Forms of Instruction. We define *collaborative instruction* to apply to all methods in which teachers and students abandon their traditional classroom roles in favor of more collegial roles as collaborating learners.[9] A critical feature of such methods is that not only the teacher but all students actively participate in the production and presentation of knowledge (Abercrombie, 1969). Project-Based Learning (Blumenfeld et al., 1991), and Problem-Based Learning, as described earlier in this chapter, both serve as obvious examples of collaborative instruction under this definition. Less obvious examples might also include Cognitive Apprenticeship (Collins et al., 1989) and Reciprocal Learning (Palincsar & Brown, 1984).

Collaborative forms of instruction reflect several of the principles of effective learning and instruction described earlier. A group engaged in mutual pursuit of knowledge provides a source for multiple perspectives and interpretations (Principle of Multiplicity). The power of the group to engage the student also promotes activeness (Principle of Activeness). Group participation demands articulation (Principle of Articulation) and because the individual's thoughts and ideas become apparent, challenged, and shaped, fosters adaptation (Principle of Adaptation and Accommodation). Because much of modern work depends on teams of individuals coordinating their efforts toward a common goal (Bailey, 1990), and because this is an acquired skill, collaborative methods prepare students for entry into a culture of practice (Principle of Authenticity).

Learning Organized Around Problems of Practice: Case-Centered Instruction. There is a rich and long-standing tradition, particularly in professions education, to base instruction on the realistic tasks of a field (Barrows & Tamblyn, 1980; Merseth, 1991; Williams, 1992). Recently the value of

[9]See Roschelle and Behrend (1995) and Bruffee (1993) for alternative treatments of this term.

an immersion in the culture of a domain of practice (e.g., Brown et al., 1989; Lave, 1988) and of designing conditions of knowledge acquisition so that they are similar to conditions of ultimate knowledge use and application (e.g., Baddeley, 1982; Tulving & Thomson, 1973) have reinforced this intuition. Furthermore, some have made the strong claim that the very nature of expertise in complex, ill-structured domains consists of reasoning by analogy from a set of past cases (Norman & Schmidt, 1992; Riesbeck & Schank, 1989).

Case-centered instruction and associated approaches, such as *anchored instruction* (Bransford et al., 1990), incorporate a number of the Principles of Effective Learning and Instruction. Learning organized around realistic tasks of a field is the epitome of authenticity (Principle of Authenticity). Energy generated, both as learners are caught up in the problem-solving process and as they are excited by the relevance of both the process and the outcomes of learning (cf. Blumenfeld et al., 1991), helps engage the students in the learning process (Principle of Activeness). When instruction is oriented toward cases or problems, it becomes harder to avoid or gloss over the complexity of what is being learned. Learners are consequently forced to confront the irregularity and "messiness" in cases and to contend with multiple meanings and multiple legitimate interpretations of information in context (Principle of Multiplicity). Finally, as learners acquire and organize knowledge around cases, they develop an awareness that knowledge is fallible, that it supports tremendously different levels and types of understanding, that statements written in textbooks by experts are sometimes wrong (Coulson et al., 1989), and that it is easy to be deceived into thinking one understands better than one actually does—the essence of skeptical uncertainty (Principle of Termlessness).

Allowing Students to Exercise Greater Control Over Their Learning: Learner-Directed Instruction. In traditional approaches to education, the responsibility for learning lies with the instructor. Teachers and curriculum designers had defined as their responsibility identifying, to a high degree of precision, just what the student needs to know, specifying the behavior that would certify reaching the objective, and specifying the context in which that behavior should be evaluated (Gagné, 1972; Mager, 1962; Merrill, 1982). The recognition that such precision and orderliness exists only where artificially produced and an awareness of the problems associated with fostering such a teacher-dependent approach to learning have led to the realization that students, who are the products of such educational methods, are not prepared to function independently in the real, complex, unpredictable world beyond the classroom (e.g., Feltovich et al., 1989, 1992). Out of such considerations has emerged the movement toward learner-directed education, in which students are charged with the responsibility for much of their own learning (e.g., Barrows & Tamblyn, 1980; Thomas & Anderson, 1991). In learner-directed instruction, the student must identify what he or she needs to know, what resources are needed, and the most effective and efficient use of those resources. Finally, the student must critique the validity and relevance of the information that is encountered in light of the goals toward which the effort was directed, working out the process by which mid-course corrections toward the goal are to be made. Faculty responsibilities include helping students identify what knowledge they bring to the learning situation, and what knowledge will advance them toward the goal; modeling and coaching the appropriate attitudes and behavior toward knowledge and learning; providing general curricular scaffolding to guide students toward some broad educational goal (e.g., becoming a physician); confirming, challenging, and clarifying student-expressed ideas in the faculty member's area of expertise, and providing external feedback on the student's progress toward educational goals (cf. Collins et al., 1989; Greenfield, 1984).

The Principles of Activeness, Accommodation, and Termlessness are at the heart of learner-directed teaching. Learning in such a curriculum emanates from the learner's need to know and is designed to maximize the shaping of knowledge to the learner's needs. Learner-directed instruction is especially designed to encourage the development of a disposition toward, and competency in, self-directed learning. The learner also encounters multiple perspectives, disagreements, and changing ideas (Principle of Multiplicity) in the course of learner-directed teaching, the key to developing skeptical certainty.

Problem-based learning contains elements of all three of these categories of instructional methodology (e.g., collaborative, case-centered, and learner-directed instruction) and in some sense could be viewed as an instance of each. Many of the features of PBL that complicate its full realization in the classroom are shared by these related methods. For example, the requirements of the PBL group working as a team (e.g., overcoming the undesirable features of group discussion, the need for better records of the group's deliberations, the need to attribute participant's contributions) are requirements of all collaborative methods that depend on group problem solving. Further, the requirements pertaining to the construction of authentic cases (the fidelity and cueing problems) and the problems of organizing and indexing case notes are requirements that will arise in any method that is case-centered. Finally, the requirements of students as individual learners (the need to facilitate access to learning resources and ensure that students do not harbor misconceptions) also apply to other methods that depend upon learner-directed teaching. Consequently, it can be argued that many of the technological enhancements that have been planned or introduced into PBL may also find application in other methods that share its essential characteristics.

A Principled Approach to the Design of CSCL Tools

The preceding narrative offers a case study of how one might go about developing tools to support a particular form of collaborative instruction. We offer it as an example of a principled or theory-based approach to the design of technologies for CSCL. Our presentation followed the four steps of theory-based design enumerated in the introduction. We recapitulate that process here.

The first step in a theory-based design is to articulate the desired instructional features of the planned innovation. For this case study, these features were specified in the form of six principles—each consisting of a description of what constitutes robust and flexible learning in complex and ill-structured domains, and a prescription for how to achieve it through instruction. This list of principles, therefore, represents both a model of effective instruction and the design goals for the project being described.

The second step is to analyze current practice in the light of the design goals. The purpose of this analysis is to determine aspects of current practice which are suboptimal with respect to the instructional goals, particularly aspects that may be remediable through the introduction of technology. This analysis was performed by analyzing PBL with respect to the six principles.

CSCL designers should be aware that the success of a project may be jeopardized if the planned innovation is too discordant with current practice. Instructional initiatives may fail, for example, because the underlying theory of instruction may not appeal to the instructor, the students, or both. In recent studies of the use of the computer-mediated communication in college composition classes, Moran and Klem (1992) reported that some teachers rejected a computer-based writing tool because of the changes it entailed in the teacher's role in the classroom. The project described in this chapter has benefited from the fact that the technological innovation does not introduce a new theory of instruction into the setting, but instead supports and extends a method of instruction that has already been accepted by faculty and students.

The third step in the design process is to develop a specification based on both the instructional requirements of the setting and the known capabilities of the proposed technology. Because the design is driven from the outset by instructional requirements rather than the features of a new technology, the fit between existing technology and the needs of the classroom may not always be perfect. In these situations, the technology must be adapted to meet these needs, or the design process will regress into one that is essentially technology-driven. In the current project, available technologies (e.g., e-mail and access to electronic informational resources) could only accommodate some of the identified instructional requirements. Additional technologies (e.g., the Collaborative Learning Laboratory and the Electronic Case Notebook) were required to satisfy the design goals.

The fourth and final step of the design process is to produce an implementation that allows for adaptation to instructional practice. Developers of instructional software (CSCL-related and otherwise) must try to accommodate variability across classrooms by designing their systems to be sufficiently flexible to support differences in local patterns of use. Indeed, the best tools may be the ones that can be reinvented by their users, that "co-evolve" with practice (Suchman & Trigg, 1991). Bruce and Peyton (1991) referred to the divergent ways in which identical software tools were used by students and instructors in different settings as *realizations*. We must recognize that the emergence of a variety of such realizations does not constitute a dilution of the original design, but, rather, an enrichment through creative use.

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