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Design Principles for Distributed Knowledge Building Processes

Jim Hewitt[1] and Marlene Scardamalia

In this paper we explore various interpretations of the term "distributed cognition," then turn our attention to communities grounded in the practice of collaborative knowledge building. We discuss CSILE (Computer-Supported Intentional Learning Environments), a technology designed to support contributions to a communal database. Shared responsibility for this community resource extends to aspects of school practice typically handled exclusively by teachers, and engagement in improving and connecting the contents of the database makes the process of knowledge building self-sustaining. We discuss knowledge building communities involving students and teachers, and end with discussion of design principles for distributed knowledge building processes.

KEY WORDS: learning environment; distributed cognition; knowledge building.

INTRODUCTION

The conventional notion that cognition resides "in the head" is currently being challenged by a perspective of cognition as distributed over both individuals and their surrounds. Proponents of this view point out that human activity is heavily influenced by local affordances, which include artifacts and other people. Lave (1988) for example, suggests that the relationship between human thought, human action, and the environment is so tightly interwoven that the mind cannot be studied independently of the culturally organized settings within which people function. Individuals and their surroundings comprise a system of cognition that can neither be fully appreciated nor fully understood through reductionist methods. From this point of view, the tools, rules, values and actors in a classroom constitute

[1]Centre for Applied Cognitive Science, Ontario Institute for Studies in Education, Toronto, Canada.

a highly complex, interacting system. Textbooks, notebooks, rulers, the organization of desks, and the writing on blackboards and bulletin boards are seen as cultural artifacts that carry intelligence in them (Pea, 1993). Other, more social distributions may be observed in a student's guided participation in advanced activities or in the conversations of classmates working together collaboratively (Hatch and Gardner, 1993). For over a decade our research has been exploring the implications of distributed cognition for schooling and educational practice. What kinds of distributions facilitate learning? And how can technologies be harnessed to support educationally effective distributed processes?

In this paper we explore uses of the phrase "distributed cognition" then turn our attention to schooling and to communities grounded in the practice of collaborative knowledge building. We discuss design features of the CSILE (Computer-Supported Intentional Learning Environments) technology which aims to support the Knowledge-Building Community model and activities that make these communities self-sustaining. We also discuss the extension of this model to teachers working over the Internet, and end with discussion of design principles for distributed learning processes.

WHAT IS DISTRIBUTED COGNITION?

Conceiving of cognition as distributed is counterintuitive in many respects. People think of cognition in terms of internal, intangible mental processes that, by their very nature, are incapable of being shared with other individuals or with the artifacts in one's environment. On the other hand, references to communal cognition are common in everyday speech. Phrases like, "We know how to send an astronaut to the moon," suggest that cognition can be conceptualized in collective terms. But what does it mean to say that a group of people know something? And what does the word *distributed* mean? An investigation of the literature reveals many conflicting responses to these questions. For clarity, we examine the concept of distributed cognition from three perspectives: a situative perspective, a cognitive perspective, and a combined perspective.

Distributed Cognition: A Situative Interpretation

Proponents of the situative perspective (Lave, 1988; Lave and Wenger, 1991) claim that much or all of what is learned is tied to the specific situation in which the learning takes place. This idea grew, in part, out of a series of key studies that investigated people's use of mathematics in nonschool settings. The research examined how Brazilian street vendors (Carraher *et al.*, 1985), dairy case loaders (Scribner, 1984), supermarket shoppers (Lave, 1988) and other "just plain folks" solved problems involving calculation. Mathematical activity, it was suggested, was guided more by situational constraints and affordances than by the formal mathematics taught in school. Doing mathematics, Lave proposed, takes on radically different forms in different contexts (Lave, 1988). The issue is not simply that in-the-head knowledge is selectively tailored to meet the particular needs of each situation, but that the affordances and constraints of a situation are an inseparable part of the cognitive process. This tight binding between in-the-head representations and in-the-world activity suggests that cognition should be viewed as *distributed* over mind, body, and the surrounds. The term "distributed," in this case, does not mean "divided up" in the sense that candies are distributed to children at a party. Rather it means "spread over," much in the same way that weather systems cover a geographical area. A weather forecaster may point to low pressure cells, high pressure cells, storms, and clear skies on a weather map, but these are not isolated meteorological phenomena. Each of these continually affects the others. In a similar fashion, the mind, the setting, activity, artifacts, signs, symbols, social processes, and cultural factors comprise a mutually interacting, interdependent, and indivisible system of cognition (Greeno, 1997). Thus, from a sociocultural point of view, individual mental processing is better understood as a complex system involving the individual and the whole personal environment. All cognition is fundamentally situated and distributed.

An important extension of the situative perspective is a line of thinking that focuses almost exclusively on social distributions. Grounded in Vygotskian theory, this approach suggests that knowledge exists in the way that social groups communicate, make use of symbols and tools, and organize their belief systems. Understanding is no longer a process of coming to know the entities and attributes that exist in the world, but one of successfully negotiating the meaning of these objects with others. This is achieved by taking a legitimate role in the ongoing activities of a community and gradually moving to fuller participation (Brown, Collins, and Duguid, 1989). Collins *et al.* (1989) have begun to investigate the educational ramifications of Vygotskian theory by devising an instructional model called cognitive apprenticeship. At the heart of cognitive apprenticeship is the notion of a "zone of proximal development" (Vygotsky, 1978)—a zone of cognitive processes that are just beyond the student's immediate capabilities. The idea is that the teacher and student collaboratively work on activities in this zone, with the teacher gradually transferring responsibility for activities to the student as competence develops.

Distributed Cognition: A Cognitive Interpretation

Cognitive analysis postulates that knowledge exists in the head, and that learning is a process of ongoing cognitive reorganization. The focus is on the individual's internal intellectual structures, with in-the-world activity serving as input to mental processes through the sensory-motor channels. This view is consistent with the situative position, that activity is an important part of learning, but in the cognitive case a strong distinction is made between "knowing" and "doing" rather than viewing the two as completely interdependent and inseparable. Some knowledge is specific to in-the-world situations, while other knowledge is contextually independent (Anderson *et al.*, 1996). Reading is an example of a skill that transfers easily across domains and is thus contextually independent.

From a strictly cognitive perspective, the notion of distributed cognition is ill-defined. If cognition is interpreted as an in-the-head phenomenon, then how can cognition be distributed across people or objects? Nickerson (1993) raises the following concerns:

> Are we saying that the group, as an entity, knows something? And if we are saying that a group, as such, knows X, what might that mean? That one or more members of the group know X? Suppose that one member of the group knows X while all the other members believe not-X; would we say that the group knows X?
>
> When we say that the group knows X and Y, even though no single member of the group knows X and Y, are we saying that at least one person in the group knows X and at least one other knows Y? Suppose those members who know X believe not-Y and those who know Y believe not-X; would we say that the group, as such, knows X and Y? Should we say that a group knows X only if a majority of the group"s members know X? If we do this, we leave open the possibility of the group knowing less than some of its members. (p. 233)

Some of Nickerson's uncertainties may be equally applicable to individual cognition. For instance, a child can know X (that the Earth is round) and not-X (that everyone walks on the same seemingly horizontal plane) at the same time. Similarly, a researcher may adopt the pragmatic perspective that knowledge and learning are fundamentally situated for some purposes, and in-the-head for other purposes (Cobb, 1994). Both individuals and groups can accommodate two or more sets of ideas that, under analysis, reveal themselves to be mutually incompatible. Thus Nickerson's problem of defining what it means for a group to know something may not be far removed from the problem of defining what it means for an individual to know something.

Rather than dwell on how to interpret "group knowing," many theorists focus on what it means for the construction of knowledge to be distributed. Consider, for example, a conversation between two people who are trying to solve a problem. Conversations typically involve a back-and-forth exchange in which each utterance is tied, either implicitly or explicitly, to the utterances that preceded it. Discourse is dynamic; none of the participants know with absolute certainty where a particular thread will lead or what new ideas will emerge. This co-construction of a progression-of-thought is one interpretation of the phrase "distributed cognition" from a cognitive point of view. Each person's individual cognitions are continually reorganized in an effort to construct meaning out of the other person's speech acts.

Another cognivist concern relates to the meaning—and even meaningfulness—of the concept of materially-distributed cognition, or cognition distributed across artifacts. Objects in our environment support cognition in important ways. As Pea (1993) explains:

> On close inspection, the environments in which humans live are thick with invented artifacts that are in constant use for structuring activity, for saving mental work, or for avoiding error, and they are adapted creatively almost without notice. These ubiquitous mediating structures that both organize and constrain activity include not only designed objects such as tools, control instruments, and symbolic representations like graphs, diagrams, text, plans, and pictures, but people in social relations, as well as features and landmarks in the physical environment. Imagine the absence of the following resources and the detrimental effects of that absence on the activities to which they may contribute intelligence: keyboard letters, labels on instrument controls, everyday notes, well-placed questions, the use of space to organize piles of materials on a desktop, the emergent text in a written composition that one is constructing (Pea, 1993, pp. 48-49).

While we may acknowledge that the letters on a keyboard help us type, it is a larger step to suggest that people engage in cognitive partnership with those letters. If such a partnership is possible, it may be a qualitatively different one than the kind that occurs between individuals. The notion that there may be different kinds of distributed cognition has been suggested by Salomon (1993) who proposed that there are at least two classes. The first class consists of cognitions that are distributed through shared activity, such as the problem-solving conversation described above. The second class, called off-loading, is the one more commonly used to describe material distributions (although one also can off-load onto other humans). For example, a shopping list supports the cognitive task of remembering what groceries need to be purchased. A calculator helps with arithmetic operations. A folder placed by the door serves as a reminder to bring the folder to work. A car dashboard reduces some of the complexity of driving. And so on. Interestingly, people are rarely conscious of all the ways in which they use the tools around them to offload cognitive effort. Tools that afford off-loading become almost invisible, which incidentally is what off-loading is all about—people do not want to invest mental resources trying to open doors, turn on faucets, or adjust the volume on the radio. That is why a well-designed door handle makes door-opening an intuitive and almost unconscious process. The strengths and weaknesses of door handle designs only become apparent when difficulties arise (Norman, 1988).

What is uncertain about "off-loading" is how to interpret the artifact's role in a cognitive distribution. One approach is to claim that knowledge is embedded in the object itself. The design of a door handle, for instance, suggests pulling, pushing, or turning, just as stairs suggest climbing or a hammer suggests hammering. Design is thus conceived as objectified knowledge. However, under closer scrutiny, problems become evident. Consider the example of a string tied around a person's finger as a reminder of an upcoming event (say a birthday). The string eases the task of remembering the birthday, but there is nothing particularly "birthdaylike" about the string itself. In fact, the string is meaningless to everyone except the person wearing it. In a similar fashion, any tool, well-designed or not, may be meaningless to a person unfamiliar with that tool and its function. Artifacts *mediate* cognition, but they do not *do* cognition (Pea, 1993), and it is not clear in what sense they *contain* knowledge (see Anderson *et al.*, 1995, for further discussion of this last point).

Distributed Cognition: A Combined Interpretation

The tension that exists between the cognitive and situative interpretations is rooted in a disagreement concerning the nature of cognition. The former presupposes a container model (Bereiter and Scardamalia, 1996), in which the mind is viewed as a container for cognition. Situative theory, on the other hand, proposes that cognition emerges when people, objects, and situations combine. Cognition is spread over the entire situation, and it can not be reduced to chunks of cognition that are located in the head or in an object. This interpretation has a simplicity that is appealing, though incompatible with the conventional notion that cognition exists as internal mental representations. Consequently, there have been attempts to combine portions of the situative and cognitive arguments. For instance, Salomon (1993) proposes two varieties of interacting cognition: one individual and one distributed:

> In this light, it can be argued that, although cognitions can be and often are distributed, that human action is indeed contextual and that the Heideggarian argument of thrownness-in-the-world may have conceptual appeal, nevertheless these are but "stations" in an ongoing developmental process: Distributed cognitions, thrownness and contextual actions interact with those elements one traditionally attributes to the mind of the individual: mentally represented knowledge and skill. (p. 120)

Salomon suggests that individual and distributed cognitions interact in a spiral-like fashion, with distributed cognitions informing individual ones, and individual cognition affecting distributed practices.

A distinction between individual and distributed cognitions is also made by Pea (1993) who uses the term distributed intelligence to refer to the latter. Distributed intelligence focuses on situated, moment-by-moment interactions—what people do in their day-to-day lives. It involves planning, inventing artifacts, reorganizing existing artifacts to facilitate future personal and communal activity, and so forth (Pea, 1993). We know little about how and why communal artifacts are developed, and Pea recommends greater study of the inventive process that gives rise to social and material distributions.

Both Pea and Salomon propose theoretical frameworks that interweave individual cognitions with cognitions (or "intelligences" in Pea's case) that are situationally-based and grounded in activity. The challenge facing these integrative approaches is to find ways to bring together two different philosophies concerning the nature of knowledge.

DISTRIBUTED COGNITION AND EDUCATIONAL CHALLENGES

In this paper, we focus on educational implications of individual- and community-level processes that arise when the classroom is viewed through the lens of distributed cognition. It is tempting to paint a picture of a cognitivist classroom with individuals working silently in their seats, employing individual testing and grading practices. The situative classroom, in contrast, has students collaborating and engaged in group work. These contrasting images are overdrawn: in even the most conservative, individual-centered classrooms, much of what goes on can be conceptualized as a distributed process of one sort or another, and ideas such as students taking greater responsibility for their learning and conducting their work in collaborative contexts is part of the rhetoric of all. At the same time, the notion that students should take charge of the highest-level regulatory functions of the classroom—functions such as evaluation of progress in understanding, curriculum coverage, and so forth—are still considered the exclusive domain of teachers and curriculum experts. The challenge is to identify the *kinds* of distributions that are educationally effective, and then to search for ways that they can play a more central role in day-to-day classroom activities.

Greater distribution of regulatory processes—including those related to curriculum goals and assessment of progress—have been the concern of the CSILE (Computer-Supported Intentional Learning Environments) initiative. We see the central challenge in distributed learning processes as resting with the ability to monitor progress and refine goals, not simply distributing tasks and sharing ideas. Participants in a knowledge-building community must take charge of high level process for knowledge advancement—both personal and group achievements. The Knowledge Building Community model was developed to enable this.

The Knowledge-Building Community Model

In a broad sense, a Knowledge-Building Community is any group of individuals dedicated to sharing and advancing the knowledge of the collective. Research teams in the scientific disciplines provide a prototypical example, although Knowledge Building Communities also can exist as film societies, literary cliques, industrial firms, and even some families (Scardamalia and Bereiter, 1994). What is defining about a Knowledge-Building Community is not formal association (e.g., "Department," "Club," "Company") or physical proximity (although that is often important) but a commitment among its members to invest their resources in the collective upgrading of knowledge. Extended to a classroom setting, the Knowledge-Building Community model is different from contemporary school practices in several respects:

Classroom Activity Defined by Advances in Knowledge Rather than Completion of Tasks

Most classrooms can be characterized as "task-based" because the focus is on completing tasks such as story-writing, project-building, math exercises, and so forth. In comparison, the focus of the Knowledge Building Community is on advancing knowledge. Conventional school tasks may still be involved, but these are now subordiante to engagement in a collaborative research program with the goal of advancing both individual and collective understanding. Participants develop greater competence in a particular subject area, using what group members already know as an important component, and co-constructing plans of action to extend that knowledge. Much like an academic research community, this involves talking to more knowledgeable colleagues, reading relevant resource materials, posing questions, offering theories, conducting experiments, and generally working with peers to make sense of new ideas. Individual understanding is thus driven forward by the dual need to be familiar with the knowledge of others and to advance that knowledge (Scardamalia and Bereiter, 1997).

Greater Access to Distributed Expertise

Within a typical classroom of 20–30 students there is a wealth of untapped knowledge and expertise. Unfortunately, fully exploiting this resource is difficult given the time-consuming task of discovering where expertise lies, and figuring out how to take advantage of it. As a result, many opportunities for the productive distribution of cognitions are lost. The Knowledge-Building Community model attempts to solve this problem through technological supports. As networked computer systems make their way into school classrooms, they provide us with opportunities to redesign the kinds of distributions that go on there. One notable and unique aspect of local-area and wide-area network technology is its ability to allow a large number of people to work simultaneously in a common environment on common problems. This "many-to-many" form of communication bypasses many of the logistical limitations associated with large group, face-to-face discourse, providing opportunities for distributed processes that would normally not be possible.

Student-Created Artifacts as Mediators of Distributed Cognition

Humans continually modify their surroundings to help them organize and streamline activity (Pea, 1993). Sometimes this involves the creation of new artifacts, while at other times it simply requires the reorganizing of artifacts that already exist. The earlier examples of writing a report at one's workplace, maintaining a grocery list, or placing a folder by the door, are all instances of manipulating objects to scaffold personal and group activity. This is the initiating, or designing, end of distributed cognition. The culture of schools, however, is one that de-emphasizes this design process (Pea, 1993). There are physical outputs of classroom work (tests, essays, projects, reports), but these are typically handed to the teacher for evaluation and either put on display or returned to the student. In either case, they are not likely to be referred to again. Thus, while students go through the motions of creating new artifacts, they fail to reap the benefits of using them as cognitive tools. Rather than "teaching for the design of distributed intelligence," as Pea (1993) recommends, schools set up artificial situations that fail to convey the personal and communal advantages of actively distributing knowledge. To address this deficiency, student-created artifacts in a Knowledge-Building Community are made available to the entire class. Using a collaborative online environment, each student's ideas are stored as electronic documents in a publicly-accessible database, and can be subsequently used as a foundation for other, more advanced artifacts. In this manner, student work is valued as an intellectual resource for the entire classroom community.

In summary, the goal of a classroom-based Knowledge-Building Community model is to do justice to the ideas of others and to make the ideas of group members available to all. It is a dynamic and generative community of practice, with greater decentralization than suggested by classroom processes which are highly centralized, with all activities directed and evaluated by teachers. Resnick (1991) points out that many efficient systems in nature are of a form in which none of the individual parts manages the activity of the whole. He suggests that people tend to bring a "centralized mindset" to problems of organization and task completion, and overlook the possibility of building more autonomous, self-organizing systems. The Internet, especially in the development of the World Wide Web, is an example of powerful decentralized activity on a large scale. To establish a Knowledge- Building Community in the classroom, we need to support the conceptual and cultural shift from dependence on centralized systems to more distributed systems that not only have students taking more responsibility for their learning, but doing so in ways that achieve educational excellence.

CSILE: Computer Supported Intentional Learning Environments

CSILE (Scardamalia *et al.*, 1989) attempts to facilitate student work in a "many-to-many" environment. Technically, it consists of a client application running on computer workstations, and a multimedia database that contains the ongoing research of the class. In many classroom-based systems of this sort, each student's work is segregated into a separate folder or account. CSILE takes the opposite tack and places all files (which in CSILE are called "notes") in a common area. All notes are publicly readable by the entire class. Through use of linking and commenting mechanisms, connections can be established amongst and between text and graphics notes, allowing students to build on each other's ideas. Discussions permit more structured group, or class-wide, discourse about a particular problem of understanding. Figure 1 presents a typical discussion window, with a student's problem represented at the top of the window, and classmate responses recorded in chronological order below.

The entire database of notes can be explored using search and browse facilities that are built into the client. The search interface permits students to retrieve notes by specifying the name of an author, the name of a note topic, note key words, thinking types, or any one of several other variables. Database browsing occurs through a "Knowledge Map" utility which provides a graphical overview of the notes written in a database topic (Fig. 2). Rectangles on the Knowledge Map represent discussions, squares represent graphics, and circles represent text notes. Different colored lines represent different types of connectivity between notes. A single click on a note icon provides title and author information on the Knowledge Map

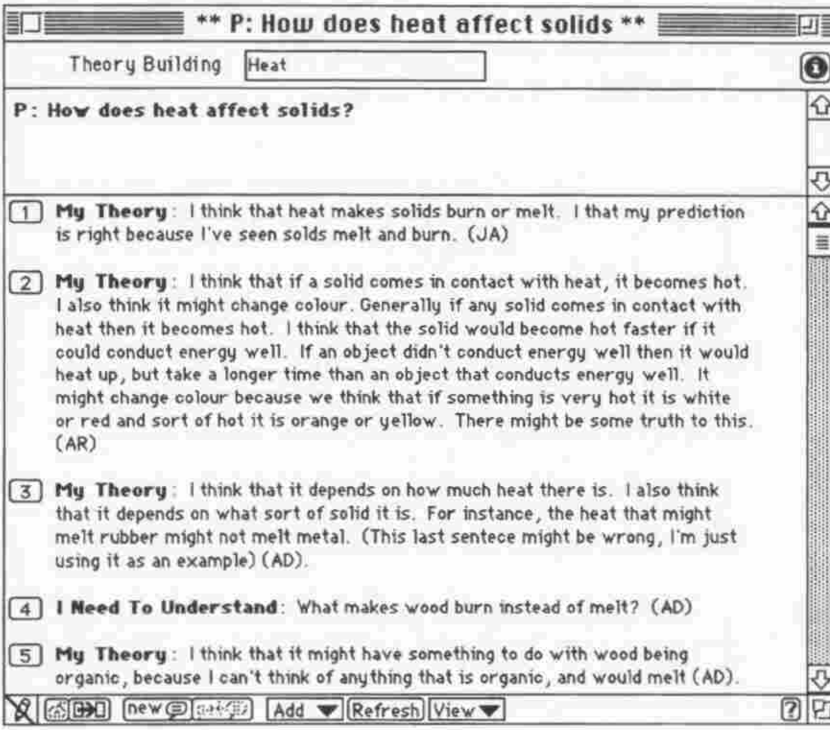

Fig. 1. A CSILE discussion.

information line. Double-clicking on a note icon causes the contents of the note to be displayed in a window.

Using the search and browse functionality, the work of the entire class is made available to all. CSILE provides a permanent record of community interaction. This allows all students to work simultaneously and permits a type of highly intensive and opportunistic peer collaboration that would be impractical, and chaotic, without computers. It also allows for asynchronous communication, and this provides time for reflection and quiet moments needed for demanding intellectual activity.

DESIGNS FOR SUPPORTING DISTRIBUTED PROCESSES

For over a decade we have been engaged in a twofold design process involving the ongoing refinement of the CSILE software package, and the ongoing reworking of teacher and classroom practices. Both processes are

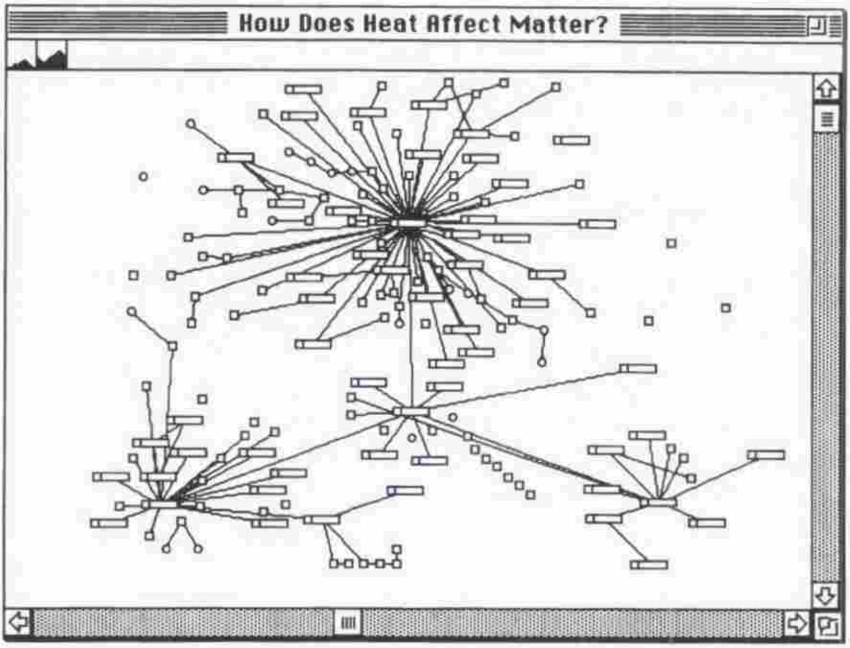

Fig. 2. A knowledge map: magnification 1.

viewed as part of the same integrated effort to create a culture of classroom knowledge building. Over time, we have identified a number of general strategies that seem particularly effective in fostering educationally-beneficial distributed practices.

1. Support Educationally Effective Peer Interactions

As Damon (1991) points out, the quantity and quality of learning that emerges out of a particular peer interaction episode is dependent upon several interacting influences. Critical factors include the degree of perceived conflict, mutuality, and equality between participants. Low levels of mutuality and equality, or unusually high or low levels of conflict, often militate against educationally productive discourse. One goal, therefore, is to develop a framework of social support in the classroom that optimizes the conditions necessary for educationally effective peer relations.

The use of computers as a discourse medium appears helpful in this regard. Researchers of computer-mediated communication report that online environments facilitate classroom equality (Mason and Kaye, 1990). While the dynamics of face-to-face conversation may shut out individuals who are shy or soft-spoken, asynchronous, computer-supported discourse gives all students a voice, and provides time for reflection and revision before an idea is submitted for public scrutiny (Harasim, 1990). This is consistent with our experiences using CSILE. Students of all abilities in CSILE classrooms appear to contribute at similar levels (Scardamalia *et al.*, 1992; Hewitt, 1996).

While online discourse may promote equality, it is arguably less conducive to maintaining an optimal level of conflict. Sometimes it produces too little. Feenberg (1987) describes the phenomenon of communication anxiety, which occurs when people submit ideas but don't receive any immediate response. A lack of immediate feedback makes it difficult for writers to know whether their contributions have been read and have value for others. At other times, written criticism may read more harshly than the writer intended, giving rise to conflict. Without the real-time, aural and visual cues of face-to-face discourse (smiles, nods, "uh-huh," etc.) it becomes difficult for writers to know how their statements are being interpreted. "Grounding a conversation" (Clark and Schaefer, 1989; Clark and Wilkes-Gibbs, 1986) is a difficult task across media that lack copresence, visibility, audibility, and simultaneity (Clark and Brennan, 1991). Users of such environments need to invest more effort in formulating their contributions than they would otherwise.

To help deal with these issues, CSILE teachers often discuss collaboration strategies with their class. They encourage students to read and comment upon other people's work. And they illustrate effective and ineffective ways of disagreeing and criticizing. For instance, teachers might write sample sentence starters on the blackboard (e.g., "I really like your idea, but I wonder if . . ."). Students copy these down in their notebooks, and then refer to them during their CSILE sessions. The goal, of course, is not to avoid student disagreement or argumentation but to maintain a balance between too much and too little conflict. Techniques like these help finesse the problem of student inexperience in social matters interfering with the teacher's community-building efforts.

2. Integrate Different Forms of Discourse

CSILE teachers try to be sensitive to the different strengths of face-to-face conversation and online discourse, and look for effective ways of combining the two in the classroom. For instance, they may encourage groups of students to gather together around a common computer and co-construct notes. Or, they orchestrate classroom activities so that in-person conversations are more likely to make their way into the database, as one CSILE teacher explains:

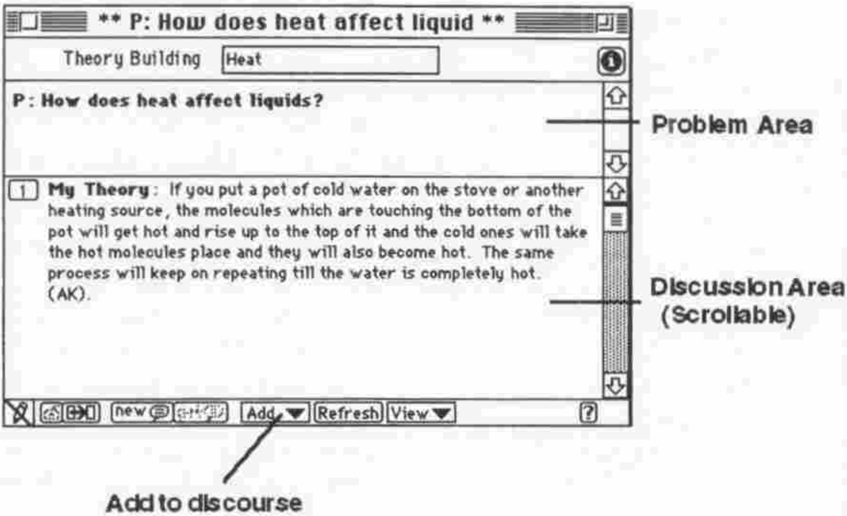

Fig. 3. A CSILE discussion.

> Because my students go to the IMC (library) first then to the computers, I find that many of the students do a lot of voluntary face-to-face discussions during their research time. They are sharing reference sources and illustrations and ideas . . . having some great conversations about their topics. I then find this conversation in a sense summarized in their databases immediately following this time. Therefore, their conversations "get" into the database . . . ; otherwise it would be lost/shared in a sense to just the few rather than the community of learners. (Cedar Rapids Iowa, U.S.)

In this way, students enjoy both the benefits of distributing cognitions through online communication (object permanence, equality, wide audience, time to reflect), and face-to-face communication (spontaneity, immediate feedback, better grounding).

3. Focus Students on Communal Problems of Understanding

Another observation from our research is that a group focus on common problems facilitates mutual scaffolding between participants. The need to come to a shared understanding places greater demands on students to clarify ideas, refine theories, answer each other's questions, and negotiate meaning with one another. One of the ways that the CSILE interface provides affordances for problem-centered discourse is through its discussion facility (Figs. 1, 3). Any class member may start a discussion by recording a personal problem of understanding in the "problem area" of the note.

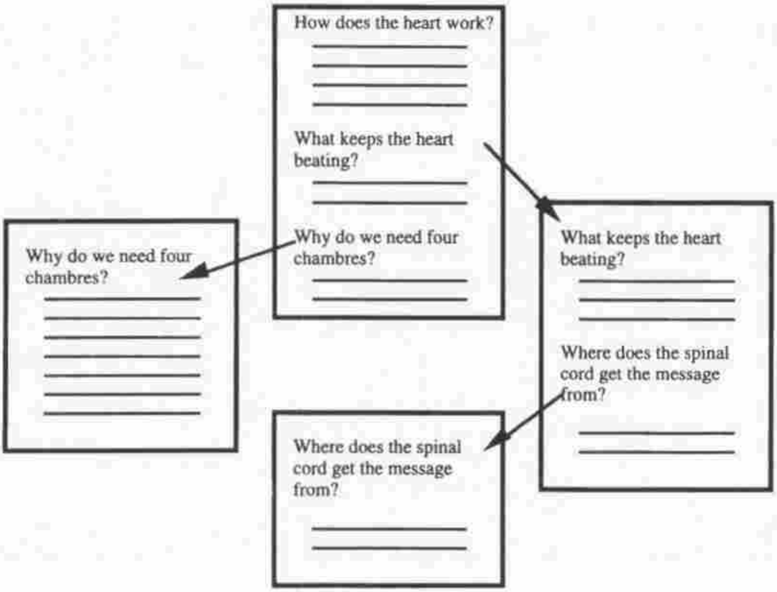

Fig. 4. A network of interconnected discussions.

The discourse itself takes place in the larger scrollable area below. All discussions are public and everyone in the class is allowed to participate.

The discussion environment also contains a special branching feature that allows students to create subdiscussions as they develop more specific queries (Fig. 4). Miyake (1986) noticed in a study of people trying to understand the functioning of a sewing machine that participants learned in an iterative fashion. As they gained understanding at one level, they would identify new conceptual problems at a more detailed level. They would then attempt to develop an understanding of that next level. In CSILE, a similar iterative pattern has been observed in which students begin with broad questions and ask increasingly detailed ones as they gain deeper collective understanding. Questions inspire new explanations, and explanations, in turn, inspire more questions. The resultant cascade of discussions is visible to students on the Knowledge Map as a web of interrelated notes. Figure 5, provides a magnified view of one Knowledge Map displaying "Heat" notes. It shows how the discussion "How does heat affect solids?" branched off into many other subdiscussions, including, "Why does sand turn into glass?" and "Why do some solids expand in heat?"

Despite these built-in CSILE supports, some teachers report that it is sometimes difficult to keep students focused on making advances on their

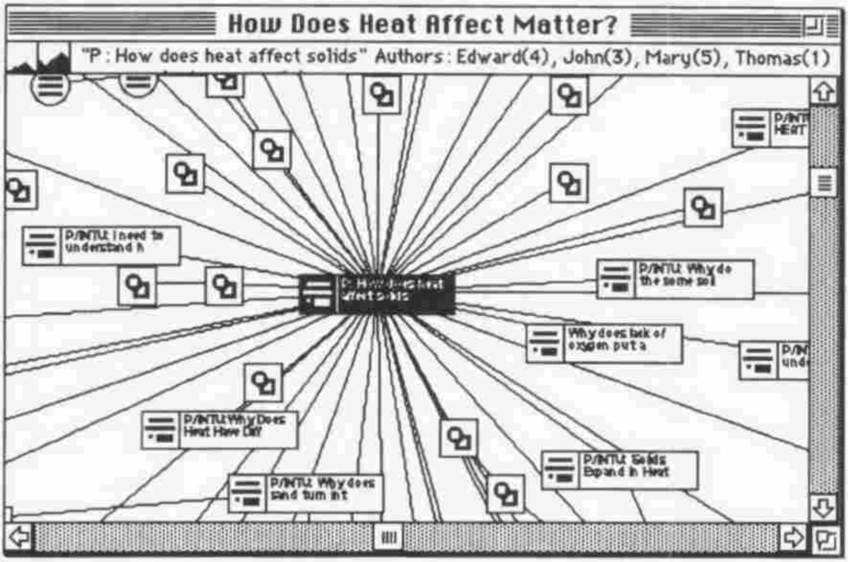

Fig. 5. A knowledge map: magnification 4 (magnification of upper-center portion of Fig. 6).

communal problems. Many students find it easier to study broad topic areas than to find answers to specific problems. As one CSILE teacher explains:

> There is a tendency to persist in topic-based "fishing trips" in the encyclopedia or other resource material. I do spend quite a bit of time with individuals asking them what problem they're working on when they're doing their research. The answer often is, "I'm working on energy" (for example), so I take that opportunity to redirect them to a problem which they are trying to solve. I explain to them how difficult it is to find information related to a specific problem and how they will have to consult many sources before they are likely to be successful. It's another attempt to move them away from the model of source material determining the direction of research, rather than the problem determining the direction of research. (Teacher, Toronto Ontario)

Thus, the teaching task is not simply one of supporting distributed processes, but is also a matter of focusing distributions in the direction of sustained collaborative inquiry by relating individual activity to pressing communal problems.

4. Promote Awareness of Participants' Contributions

In most classrooms, students rarely have a chance to read each other's work. Typically, reading time is spent on textbooks, novels from the library, the encyclopedia, and so on. This may unintentionally convey the notion

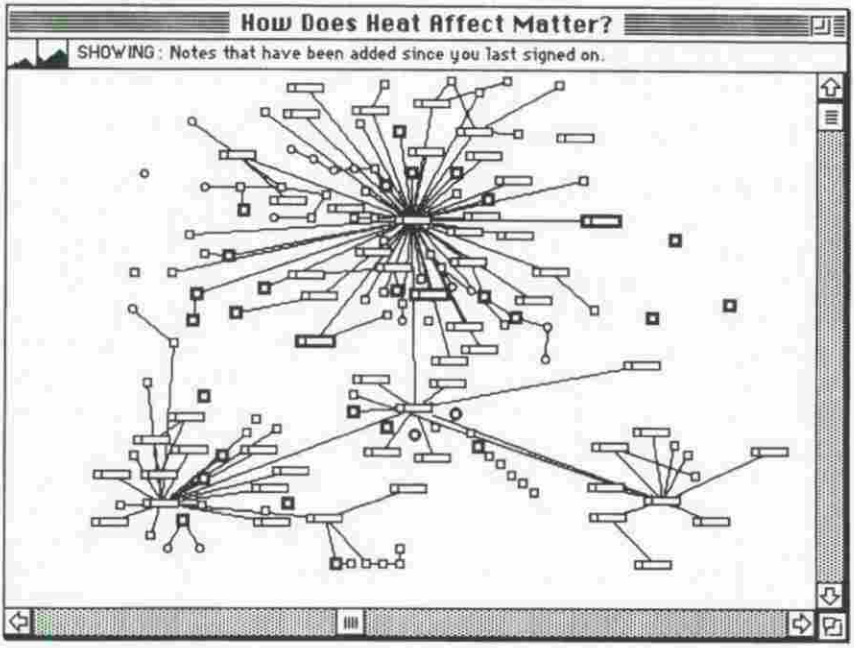

Fig. 6. A knowledge map: magnification 1. Showing new notes that have been added.

that student text is not a useful information resource (and in turn, convey to students that they are not important producers of ideas). This is an attitude that CSILE teachers continually try to change by highlighting interesting student work and encouraging database exploration. For students to take advantage of their classmates' knowledge productions they have to know that those resources exist.

Several facilities have been constructed to promote awareness and exploration of CSILE notes. One is the Knowledge Map, which provides a graphical overview of the class's notes. It includes a special function that allows an individual to see at a glance which notes have already been examined, and which notes have not (Fig. 6). Another function highlights those notes that have been introduced since the user's previous session. These features help students keep up-to-date with the growing contents of the database.

A second CSILE facility permits Boolean searches of the database. Students can retrieve notes by specifying the name of an author, the name of a topic, key words, thinking types, or any one of several other variables.

This allows students to group the notes of class in many different ways and analyze them from different perspectives.

5. Encourage Students to Build on Each Other's Work

Students have few opportunities in conventional classrooms to take up each other's work and build on it. Because these operations are unfamiliar, CSILE teachers place a great emphasis on making connections with other students. CSILE offers three ways to connect notes together, and these different types of connections are displayed as different colored lines on a Knowledge Map. Using this facility, students can see, at a glance, which notes are highly connected and which notes are isolated. Teachers, for their part, encourage students to take up each other's ideas, conjectures, and queries, and extend them through online discourse. Their goal is not simply to encourage collaboration and the efficient distribution of resources, but also for students to view their ideas as useful communal artifacts. This is consistent with the notion that students come to appreciate the personal and social advantages of designing distributed intelligence into their environment (Pea, 1993).

6. Emphasize the Work of the Community

Even with the interventions described in the previous item, it is not uncommon for some students to persist in their view of CSILE as a storage medium for individual work. These individuals find it extremely difficult to overcome the highly entrenched belief that the purpose of writing is assessment. Accordingly, our more successful CSILE teachers have adopted the strategy of focusing students on advancing the class's knowledge. The reason for this is twofold. First, by placing the individual's work in the context of a larger group mission, the teacher illustrates that the learner's own writings have value that extends beyond assessment. Second, by trying to make advances on what the group knows collectively, the student must first learn what the group already knows—and that process leads to a deeper understanding of the content and deeper appreciation of peer contributions.

Effective design components situate student work within the context of group activity. As already mentioned, the discussion environment places the user within a group discourse about a common problem of understanding. Students who enter into a discussion work on the same discourse object as other students, enter their text into the same window, and share ownership of the environment. They do not view their writings independently of other people's writings, but rather through the group artifact. At the same time the Knowledge Map provides access to individual contributions to the collective artifact. Thus rather than representing only personal contributions or only collective works, participants situate their ideas in the context of the work community. It is proposed that having students work on the same objects and in the same screen regions supports shared cognitions. Our studies have found that the common object approach both increases the quantity and quality of collaboration (Hewitt, 1996) and increases student familiarity with the work of their classmates (Hewitt and Webb, 1995).

EXTENDING KNOWLEDGE-BUILDING COMMUNITIES

Our objective in identifying design principles is to clarify means for engaging students in processes of knowledge advancement. This requires a significant reconceptualization of classroom operations. It is not enough to carry out just one or two of the above approaches—rather, it requires the coming together of many new practices. Such dramatic changes can be difficult to make. Most novice CSILE users have entrenched preconceptions that interfere with the goal of establishing a classroom-based Knowledge-Building Community. The challenge, therefore, is not simply to provide opportunities for distributed processes, because students may not even recognize them as such. Instead, the challenge is to design situations and tools that have a deliberate bias toward shared activity and rewarding interactions with other knowledge builders. This means working on shared problems of understanding, finding connections between personal work and work of peers, engaging in constructive discourse, encouraging quiet, reflective moments, and so on. This list is not complete, and CSILE research is an ongoing process of finding new ways to enculturate students into a knowledge-centered community of practice.

The CSILE team is currently extending the Knowledge-Building Community model to encompass teacher communities. Using a CSILE database running over the World Wide Web, CSILE teachers from across North America are now building a collective knowledge base of techniques and approaches for promoting collaborative knowledge-building. Their ideas span all dimensions of the classroom environment: the social, the cognitive, the affective, organizational, instructional techniques, curriculum issues, and more. A few samples taken from recent teacher discourse are provided below.

On collaboration:

> I agree that modeling is the best way to encourage commenting that is appropriate and beneficial. It does take time to develop this skill as I have personally found that students in the past have not had to do this. They were used to traditional methods where the students handed in work, the teacher corrected it and returned it to the student. Getting them to respond to others' work is a big step for them. It's a risk as they could get a response back. At the junior high level I found students

> were very aware of peer cliques. They were more likely to respond to a friend's notes than to anyone else's in the class. It was also rare for a boy to respond to a girl (and vice versa) unless they had a "thing" for them (and they knew it was reciprocal)! Perhaps it was the nature of the groups I had. Did anyone else find this? Any suggestions on how to overcome these barriers to commenting? (Baffin Island, Northwest Territories, Canada)

On use across different subject areas:

> I think that emphasizing the "scientific approach" will help both teachers and students get started on CSILE, because the system does work well in science. However, we may be doing a disservice to other disciplines, and to CSILE, if we limit our work to science. I suspect historians and scholars in other non-scientific disciplines use collaboration and knowledge-building approaches which are similar or the same as scientists. I have used CSILE in the study of history and in social science and found it works very well. In fact, it can be more challenging to define and solve problems in other disciplines because the disparity between a problem-based approach in say, history, and the organization of the source materials is even greater than it is in science. It is possible to find reference material in science which is problem-based, but it is much less common in other disciplines, especially at the level that our students can handle. Encouraging students to rise above the descriptive is very difficult, that is another reason that it would be best if a whole school were committed to a knowledge-building approach. It isn't easy to do it in one or two years. (Toronto, Ontario, Canada)

Thus, the Knowledge-Building Community idea is being tested both in the classroom and in the online community of CSILE teachers. In both cases, the goal is to make the drive for improvement become self-sustaining. By bringing together the cognitive resources of many different individuals, and by fostering a culture of progressive knowledge enhancement, we hope to support the initiative and inventiveness of these communities.

CONCLUSIONS

In this paper, we have turned our attention to the role of distributed cognition by elaborating the concept of a Knowledge-Building Community and highlighting the activities of those engaged in these communities. To work productively in such contexts, students must be able to assess their own personal knowledge needs and establish relevant courses of action. At the same time, they must understand group processes in order to assess the knowledge advances for the group as a whole and to analyze their work in light of what is being accomplished both within and outside their local community whether their community members are geographically co-located or dispersed. Such accomplishments require self- and other-regulatory processes that define the work of productive knowledge-building organizations, but are rare in schools.

To foster a classroom-based Knowledge-Building Community, we suggest that a careful interweaving of computer supports and new educational practices can bring about a more effective use of distributed resources in the classroom. Our research to-date has uncovered several approaches that seem promising. Teachers are significantly extending this research through in-class trials and through online collaborations. By developing Knowledge-Building Communities, both in the classroom and across schools, we hope to tap the synergy that emerges when distributed talents are brought together.

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REFERENCES

Anderson, J. R., Reder, L. M., and Simon, H. A. (1995). Applications and Misapplications of Cognitive Psychology to Mathematics Education. Unpublished manuscript. (http://www.psy.cmu.edu/~mm4b/misapplied.html)

Anderson, J., Reder, L. and Simon, H. (1996). Situated learning and education. *Educ. Res.*, 25(4): 5-11.

Bereiter, C., and Scardamalia, M. (1996). Rethinking learning. In Olson, D., and Torrance, N. (eds.), *Handbook of Education and Human Development: New Models of Learning, Teaching and Schooling*, Basil Blackwell, Cambridge, MA:, pp. 483-513.

Brown, J. S., Collins, A., and Duguid, P. (1989). Situated cognition and the culture of learning. *Educ. Res.* 18: 32-42.

Carraher, T. N., Carraher, D. W., and Schliemann, A. D. (1985). Mathematics in the streets and in the schools. *Brit. J. Devel. Psychol.* 3: 21-29.

Clark, H. H., and Brennan, S. E. (1991). Grounding in communication. In Resnick, L. B., Levine, J. M., and Teasley, S. D. (eds.), *Perspectives on Socially Shared Cognition*, American Psychological Association, Washington D.C., pp. 127-149.

Clark, H. H., and Schaefer, E. F. (1989). Contributing to discourse. *Cogn. Sci.* 13: 259-294.

Clark, H. H., and Wilkes-Gibbs, D. (1986). Referring as a collaborative process. *Cognition* 22: 1-39.

Cobb, P. (1994). *Where Is the Mind? Constructivist and Sociocultural Perspectives on Mathematical Development*. Paper presented at the Annual Meeting of the American Educational Research Association, New Orleans, April.

Collins, A., Brown, J. S., and Newman, S. E. (1989). Cognitive Apprenticeship: Teaching the crafts of reading, writing, and mathematics. In Resnick, L. B. (ed.), *Knowing, Learning and Mnstruction: Essays in Honor of Robert Glaser*, Lawrence Erlbaum Associates, Hillsdale, NJ, pp. 453-494.

Damon, W. (1991). Problems of direction in socially shared cognition. In Resnick, L. B., Levine, J. M., and Teasley, S. D. (eds.), *Perspectives on Socially Shared Cognition*, American Psychological Association, Washington D.C., pp. 384-397.

Feenberg, A. (1987). Computer conferencing and the humanities. *Instr. Sci.* 16(2): 169-186.

Greeno, J. G. (1997). Response: On claims that answer the wrong questions. *Educ. Res.* 26(1): 5-17.

Harasim, L. (1990). Online education: An environment for collaboration and intellectual amplification. In Harasim, L. (ed.), *Online Education: Perspectives on a New Environment*, Praeger Publishers, New York: p. 39-64.

Hatch, T., and Gardner, H. (1993). Finding cognition in the classroom: An expanded view of human intelligence. In Salomon, G. (ed.), *Distributed Cognitions*. Cambridge University Press, New York.

Hewitt, J. (1996). Progress Toward a Knowledge-Building Community. Doctoral Thesis. University of Toronto, Toronto, Canada.

Hewitt, J., and Webb, J. (1995). Knowledge Map Research Report. Unpublished manuscript.

Lave, J. (1988). *Cognition in Practice: Mind, Mathematics and Culture in Everyday Life*, Cambridge University Press, Cambridge, UK.

Lave, J., and Wenger, E. (1991). *Situated Learning: Legitimate Peripheral Participation*, Cambridge University Press, Cambridge, UK.

Mason, R., and Kaye, T. (1990). Toward a new paradigm for distance education. In Harasim, L. (ed.), *Online Education: Perspectives on a New Environment*, Praeger Publishers, New York, pp. 15-38.

Miyake, N. (1986). Constructive interaction and the iterative process of understanding. *Cogn. Sci.* 10: 151-177.

Newman, D., Griffin, P., and Cole, M. (1989). *The Construction Zone: Working for Cognitive Change in School*, Cambridge University Press, Cambridge, UK.

Nickerson, R. (1993). On the distribution of cognition: some reflections. In Salomon, G. (ed.), *Distributed Cognitions*, Cambridge University Press, New York.

Norman, D. (1988). *The Psychology of Everyday Things*, Basic Books, New York.

Pea, R. (1993). Practices of distributed intelligence and designs for education. In Salomon, G. (ed.), *Distributed Cognitions*, Cambridge University Press, New York, pp. 47-87.

Perkins, D. N. (1993). Person-plus: A distributed view of thinking and learning. In Salomon, G. (ed.), *Distributed Cognitions*, Cambridge University Press, New York, pp 88-110.

Resnick, M. (1991). Beyond the centralized mindset. In Birnbaum, L. (ed.), *Proceedings of the International Conferences on the Learning Sciences*, Northwestern University Press, Evanston, Illinois, pp. 389-396.

Salomon, G. (1993). No distribution without individuals" cognition: A dynamic interactional view. In Salomon, G. (ed.), *Distributed Cognitions*, Cambridge University Press, New York, pp 111-138.

Salomon, G. (1995). *Unorthodox Thoughts on the Nature and Mission of Contemporary Psychology*. Paper presented at the American Psychological Association, New York.

Scardamalia, M., and Bereiter, C. (1991). Higher levels of agency for children in knowledge-building: A challenge for the design of new knowledge media. *J. Learn. Sci.* 1(1): 38-68.

Scardamalia, M., and Bereiter, C. (1994). Computer support for knowledge-building communities. *J. Learn. Sci.*, 3(3): 265-283.

Scardamalia, M., and Bereiter, C. (1997). Adaptation and understanding: A case for new cultures of schooling. In Vosniadou, S., Corte, E. D., Glaser, R., and Mandl, H. (eds.), *International Perspectives on the Psychological Foundations of Technology-Based Learning Environments*.

Scardamalia, M., Bereiter, C., McLean, R., Swallow, J., and Woodruff, E. (1989). Computer-supported intentional learning environments. *J. Educ. Comput. Res.* 5(1): 51-68.

Scardamalia, M., Bereiter, C., Brett, C., Burtis, P. J., Calhoun, C., and Smith Lea, N. (1992). Educational applications of a networked communal database. *Interact. Learn. Environ.* 2(1): 45-71.

Scribner, S. (1984). Studying working intelligence. In Rogoff, B. and Lave, J. (eds.), *Everyday Cognition: Its Development in Social Context*, Harvard University Press, Cambridge, MA.

Vygotsky, L. S. (1978). *Mind and Society: The Development of Higher Psychological Processes*, Harvard University Press, Cambridge, MA.