“*Studying Online Collaborative Learning at the Math Forum*” Project Description

1. A Central Research Issue of Collaborative Learning

1.1. A Conflict of Paradigms

Research on learning and education is troubled to its core by a conflict of paradigms. Sfard reviewed some of the history and consequences of this conflict in terms of the incompatibility of the acquisition metaphor (AM) of learning and the participation metaphor (PM) (Sfard, 1998). AM conceives of education as a transfer of knowledge commodities and their subsequent possession by individual minds. Accordingly, empirical research in this paradigm looks for evidence of learning in changes of mental contents of individual learners. PM, in contrast, locates learning in intersubjective, social or group processes, and views the learning of individuals in terms of their changing participation in the group interactions. AM and PM are as different as day and night, but Sfard argues that we must learn to live in both complementary metaphors.

The conflict is particularly pointed in the field of CSCL (computer-supported collaborative learning). The term “collaborative learning” can itself be seen as self-contradictory given the tendency to construe learning as taking place in individual minds. Having emerged from a series of paradigm shifts in thinking about instructional technology (Koschmann, 1996), the field of CSCL is still enmeshed in the paradigm conflict between opposed cognitive and sociocultural focuses on the individual and the group (Kaptelinin & Cole, 2002). In a keynote at the CSCL ’02 conference (Stahl, 2002f), Koschmann argued that even exemplary instances of CSCL research tend to adopt a theoretical framework that is anathema to collaboration (Koschmann, 2002a). Koschmann recommended that talk about “knowledge” as a thing that can be acquired should be replaced with discussion of “meaning-making in the context of joint activity” in order to avoid misleading images of learning as mental acquisition and possession.

Although Koschmann’s alternative phrase can describe the intersubjective construction of shared meanings achieved through group interaction, the influence of AM can re-construe meaning-making as something that must perforce take place in individual human minds, because it is hard for most people to see how a group can possess mental contents. In a paper at CSCL ’03 responding to Koschmann’s earlier keynote, the PI argued that both Koschmann’s language and that of the researchers he critiqued is ambiguous and is subject to interpretation under either AM or PM (Stahl, 2003c). A simple substitution of wording is inadequate; it is necessary to make explicit when one is referring to individual subjective understanding and when one is referring to group intersubjective understanding – and to make clear to those under the sway of AM how intersubjectivity is concretely possible.

The problem with recommending that researchers view learning under both AM and PM or that they be consistent in their theoretical framing is that our common sense metaphors and widespread folk theories are so subtly entrenched in our thinking and speaking. The languages of Western science reflect deep-seated assumptions that go back to the *ideas* of Plato’s *Meno* and the *ego cogito* of Descartes’ *Meditations*. It is hard for most people to imagine how a group can have knowledge, because we assume that knowledge is a substance that only minds can acquire or possess, and that only physically distinct individuals can have minds (somewhere in their physical heads).

1.2 Evidence to Overcome the Conflict

We (the PI, co-PIs and collaborators in this project) propose to address this central research issue head-on by studying online collaborative learning in the specific context of Math Forum problems, with the aim of presenting empirical examples of concrete situations in which groups can be seen to have knowledge that is distinct from the knowledge of the group members. By analyzing these situations in detail, we will uncover mechanisms by which understanding of mathematics passes back and forth between the group as the unit of analysis and individual group members as units of analysis.

One example might be a group of 5 high school students collaborating online over a two week period. They solve an involved algebra problem and submit a discussion of their solution to the Math Forum. By looking carefully at the computer logs of their interactions in which they collaboratively discussed, solved and reflected upon the problem, we can see that the group solution exceeds the knowledge of any individual group members before, during or after the collaboration. For instance, there may be some arguments that arose in group interaction that none of the students fully understood but that contributed to the solution. Or a mathematical derivation might be too complicated for any of the students to keep “in mind” without reviewing preserved chat archives or using an external representation the group developed in an online whiteboard. By following the contributions of one member at a time, it may also be possible to find evidence of what that student understood before, during and after the collaboration, and thereby to follow individual trajectories of participation in which group and individual understandings influenced each other,

While we do not anticipate that group knowledge often exceeds that of all group members under generally prevailing conditions, we hypothesize that it can do so at least occasionally under particularly favorable conditions. We believe that we can set up naturalistic conditions as part of a Math Forum service and can collect sufficient relevant data to demonstrate this phenomenon in multiple cases. The analysis and presentation of these cases should help to overcome the AM/PM paradigm conflict by providing concrete illustrations of how knowledge can be built through group participation as distinct from – but intertwined with – individual acquisition of part of that knowledge. It should also help to clarify the theoretical framing of acts of meaning-making in the context of joint activity.

We believe that the theoretical confusion surrounding the possibility of group knowledge presents an enormous practical barrier to collaborative learning. Because students and teachers believe that learning is necessarily an individual matter, they find the effort at collaborative learning to be an unproductive nuisance. For researchers, too, the misunderstanding of collaborative learning distorts their conclusions, leading them to look for effects of pedagogical and technological innovation in the wrong places. If these people understood that groups can construct knowledge in ways that significantly exceed the sum of the individual contributions and that the power of group learning can feed back into individual learning, then we might start to see the real potential of collaborative learning realized on a broader scale. This project aims to produce rigorous and persuasive empirical examples of collaborative learning to help bring about the necessary public shift in thinking.

1.3. The Range of Views on this Issue

CSCL grows out of research on cooperative learning that demonstrated the advantages for individual learning of working in groups (e.g., Johnson & Johnson, 1989). There is still considerable ambiguity or conflict about how the learning that takes place in contexts of joint activity should be conceptualized . While it has recently been argued that the key issues arise from ontological and epistemological commitments deriving from philosophy from Descartes to Hegel (Koschmann, 2002b; Packer & Goicoechea, 2000), we believe that it is more a matter of focus on the individual (cognitivist) versus group (sociocultural) as the unit of analysis (Stahl, 2003b, 2003c). Positions on the issue of the unit of learning take on values along a continuous spectrum from individual to group:

- Learning is always accomplished by individuals, but this individual learning can be assisted in settings of collaboration, where individuals can learn from each other.
- Learning is always accomplished by individuals, but individuals can learn in different ways in settings of collaboration, including learning how to collaborate.
- Groups can also learn, and they do so in different ways from individuals, but the knowledge generated must always be located in individual minds.
- Groups can construct knowledge that no one individual could have constructed alone by a synergistic effect that merges ideas from different individual perspectives.
- Groups construct knowledge that may not be in any individual minds, but may be interactively achieved in group discourse and may persist in physical or symbolic artifacts such as group jargon or texts or drawings.
- Group knowledge can be spread across people and artifacts; it is not reducible to the knowledge of any individual or the sum of individuals' knowledge.
- All human learning is fundamentally social or collaborative; language is never private; meaning is intersubjective; knowledge is situated in culture and history.
- Individual learning takes place by internalizing or externalizing knowledge that was already constructed inter-personally; even modes of individual thought have been internalized from communicative interactions with other people.
- Learning is always a mix of individual & group processes; the analysis of learning should be done with both the individual and group as units of analysis and with consideration of the interplay between them.

In this project, we take a rather strong position on collaborative learning as our working hypothesis:

- H0 (collaborative learning hypothesis): A small online group of learners can (on occasion and under favorable conditions) build knowledge and understanding that exceeds that of its individual members.

The different positions listed above are supported by a corresponding range of theories of human learning. Educational research on small group process in the 1950's and '60's maintained a focus on the individual as learner (Johnson & Johnson, 1989; Stahl, 2000b). Classical cognitive science in the next period continued to view human cognition as primarily an individual matter – internal symbol manipulation or computation across mental representations, with group effects treated as secondary boundary constraints (Simon, 1981; Vera & Simon, 1993). In reaction to these views, a number of sociocultural theories have become prominent in the learning sciences in recent decades. To a large extent, these theories have origins in much older works that conceptualized the situated-ness of people in practical activity within a shared world (Bakhtin, 1986; Heidegger, 1927/1996; Husserl, 1936/1989; Marx, 1867/1976; Schutz, 1967; Vygotsky, 1930/1978). Here are some representative theories that focus on the group as a possible unit of knowledge construction:

- **Collaborative Knowledge Building**. A group can build knowledge that cannot be attributed to an individual or to a combination of individual contributions (Bereiter, 2002; Fuks, Gerosa, & Pereira de Lucena, 2001; Hakkarainen & Lipponen, 2002; Scardamalia & Bereiter, 1996; Wasson & Morch, 2000).
- **Social Psychology**. One can and should study knowledge construction at both the individual and group unit of analysis, as well as studying the interactions between them (Daradounis, Xhafa, & Marques, 2003; Fischer & Granoo, 1995; Palen, 1999; Resnick, Levine, & Teasley, 1991).
- **Distributed Cognition**. Knowledge can be spread across a group of people and the tools that they use to solve a problem (Hutchins, 1996; Hutchins & Palen, 1998; Solomon, 1993; Wasson & Morch, 2000).
- **Situated Cognition**. Knowledge often consists of resources for practical activity in the world more than of rational propositions or mental representations (Hewitt, Scardamalia, & Webb, 1998; Polanyi, 1966; Schön, 1983; Suchman, 1987; Winograd & Flores, 1986).
- **Situated Learning**. Learning is the changing participation of people in communities of practice (Chaiklin & Lave, 1993; Graether & Prinz, 2001; Hewitt, 1997; Lave & Wenger, 1991; Prinz, 1999; Schlager, Fusco, & Schank, 2002; Shumar & Renninger, 2002).
- **Zone of Proximal Development**. Children grow into the intellectual life of those around them; they develop in collaboration with adults or more capable peers (Brown & Campione, 1994; Goldman-Segall, 1998; Hmelo-Silver, 2004; Lemke, 1990; Vygotsky, 1930/1978).
- **Activity Theory**. Human understanding is mediated not only by physical and symbolic artifacts, but also by the social division of labor and cultural practices (Engeström, 1999; Gay & Bennington, 1999; Kaptelinin, 1996; Nardi, 1996a; Nardi, 1996b).
- **Ethnomethodology**. Human understanding, inter-personal relationships and social structures are achieved and reproduced interactionally (Dourish, 2001; Garfinkel, 1967; Hall, 1999; Heritage, 1984; Koschmann & LeBaron, 2003; Stahl, 2002d; Streeck, 1996; Streeck & Mehus, 2003).

One does not have to commit to one of these theories in particular in order to gain a sense from them of the possible nature of group knowledge. We have selected a working hypothesis that is in line with these theories in general without opting for one specifically. Based on our previous empirical work, we believe that we can study the issues raised by these theories without circularity by structuring collaborative activities, varying their parameters and critically evaluating the results. By reflecting on the theoretical issues within our work, we believe we can avoid the pitfalls of theory-laden research without claiming unattainable value neutrality.

1.4. Empirical Study of Group Knowledge

The PI previously conducted a pilot study involving a group of five middle school students collaborating on a problem involving data from a computer simulation. Like many studies of collaborative learning (e.g., Hmelo-Silver, 2004; Koschmann & LeBaron, 2003) (but unlike the proposed study), this one involved face-to-face interaction with an adult mentor present. Close analysis of student utterances during an intense interaction suggested that the group developed an understanding that certainly could not be attributed to the utterances of any one student (Stahl, 2002d). In fact, the utterances themselves were meaningless if taken in isolation from the discourse and its activity context.

There were a number of limitations to the pilot study: (1) Although the mentor was quiet for the specific interaction analyzed, it might be possible to attribute something of the group knowledge to the mentor's guiding presence. (2) The digital videotape was limited in capturing gaze and even some wording. (3) The data included only two sessions, too little to draw conclusions about how much individual students understood of the group knowledge before, during or after the interaction. To overcome such limitations, the proposed study will (1) not involve mentors active in the collaborative groups – although the group will work on problems that have been carefully crafted to guide student inquiry and advice can be requested by email from Math Forum staff. (2) The online communication will be logged, so that researchers have a record of the complete problem-solving interaction. (3) Groups will be studied over a period of a couple weeks – and longer for several groups that work on a sequence of problems.

Despite its limitations, the pilot study clearly suggests the feasibility of studying group knowledge. It shows that group knowledge is constructed in discourse and that discourse analysis can "make visible" that knowledge to researchers. Student discourse is increasingly recognized as of central importance to science and math learning (Atkins, 1999; Bauersfeld, 1995; Lemke, 1990; Schifter, 1996). Discourse analysis is a rigorous human science, going under various names: conversation analysis, interaction analysis, micro-ethnography, ethnomethodology (Coulthard, 1977; Duranti, 1998; Garfinkel, 1967; Heritage, 1984; Jordan & Henderson, 1995; Mehan, 1979; Sacks, 1992; Sinclair & Coulthard, 1975; Streeck & Mehus, 2003).

The focus on discourse suggests a solution to the confusion between individual and group knowledge, and to the conceptual conflict about how there can be such a thing as group knowledge distinct from what is in the minds of individual group members (Stahl, 2003b). One way of putting it is that meaning is constructed in the group discourse. The status of this meaning as shared by the group members is itself something that must be continually achieved in the group interaction; frequently the shared status "breaks down" and a "repair" is necessary. In the pilot study, the interaction of interest centered on precisely such a repair of a breakdown in shared understanding among the discussants (Stahl, 2002d). While *meaning* inheres in the discourse, the individual group members must construct their own *interpretation* of that meaning in an on-going way. Clearly, there are intimate relationships between the meanings and their interpretations, including the interpretation by one member of interpretations of other members. But it is also true that language can convey meanings that transcend the understandings of the speakers and hearers. It may be precisely through divergences among different interpretations or among various connotations of meaning that collaboration gains much of its creative power (Stahl, 2003c). These are questions that we will investigate as part of our micro-analytic studies of collaboration data, guided by our central working hypothesis. We believe that such an approach can maintain a focus on the ultimate potential in CSCL, rather than losing sight of the central phenomena of collaboration as a result of methods that focus exclusively on statistical trends (Stahl, 2002a).

1.5. Related Issues for Investigation

Collaborative success is hard to achieve and probably impossible to predict. CSCL represents a concerted attempt to overcome some of the barriers to collaborative success, like the difficulty of everyone in a group effectively communicating their ideas to all the other members, the complexity of keeping track of all the inter-connected ideas that have been offered or the barriers to working with people who are geographically distant. As appealing as the introduction of technological aids for communication, computation and memory seem, they inevitably introduce new problems, changing the social interactions, tasks and physical environment. Accordingly, CSCL study and design must take into careful consideration the social composition of groups, the collaborative activities and the technological supports.

In order to observe effective collaboration in an authentic educational setting, we will adapt a successful math education service to create conditions that will likely be favorable to the kind of interactions that we want to study. We must bring together groups of people who will work together well, both by getting along with and understanding each other and by contributing a healthy mix of different skills. We must also carefully design mathematics curriculum packages that lend themselves to the development and display of deep math understanding through collaborative interactions – open-ended problems that will not be solved by one individual but that the group can chew on for a week or two of online interaction. Further, the technology that we provide to our groups must be easy to use from the start, while meeting the communicative and representational needs of the activities. As part of our project, we will study how to accomplish these group formation, curriculum design and technology implementation requirements. This is expressed in three working hypotheses of the project: H1, H2 and H3 listed in section 3.2.

Two further working hypotheses define areas of knowledge building that the project itself will engage in on the basis of our findings. H4 draws conclusions about the interplay between group and individual knowledge, mediated by physical and symbolic artifacts that embody knowledge in persistent forms. H5 reports on the analytic methodology that emerges from the project.

2. The Math Forum Setting of Educational Practice

The Math Forum (www.mathforum.org) is a well-established digital library for mathematics education hosted at Drexel University. Started and periodically expanded with NSF funding (see section 3.4 below), the Math Forum now serves a virtual community of about one million people, including K-12, home-schooled and college students, classroom teachers, student teachers, mathematicians and life-long learners. It provides an integrated set of resources and services. The digital library consists of well over a million web pages of organized math resources that are publicly available. Math Forum staff and volunteers mentor thousands of students, and compile online summaries of advice given. There are special programs for students, teachers and student teachers. The second most popular service is the Problem of the Week. This service posts math problems at various grade levels (K-14) in core math subjects (e.g., algebra, geometry, pre-calculus) for students to work on. Students submit their solutions and a description of how they solved the problem to Math Forum; they receive feedback; the best submissions are posted. Mentoring is also available from the popular Ask Dr. Math service.

The Math Forum is an active virtual community, marked by strong currents of changing participation (Renninger, Weimar, & Klotz, 1989; Renninger & Shumar, 1998; Renninger & Shumar, 2002a, 2002b; Shumar & Renninger, 2002). A student with little interest in math may be introduced to the Math Forum through Problems of the Week integrated into her teacher's lesson plans, and then be drawn in to explore further on her own. A person interested in math might start to participate in threaded discussions on the site, then do some mentoring and eventually contribute materials to the resource library. A programmer can download math applets, extend them and contribute back. Many teachers and student teachers join teams to develop new Problems of the Week and attend Math Forum workshops to design new services.

Math Forum leadership is interested in significantly growing community activity and participation, so that people help each other, benefit from each other's knowledge and learn together. One way to do this is to mediate between the individual as solitary problem solver and the community as a whole by encouraging and supporting the formation of small groups of collaborators. Collaborative learning in small groups seems like the best way to reap the potential of the diverse virtual community of people of all ages and backgrounds interested in mathematics.

The proposed project is designed to systematically promote the formation of collaborative groups of math learners, based on rigorous research about group knowledge building. The project will first of all explore the ultimate potential of collaboration by studying the conditions under which group knowledge can be constructed that exceeds the knowledge of the group members. Secondarily, it will study the conditions that are favorable to successful collaboration, including group composition, curriculum design and technology support.

Individual student users of Math Forum will be invited to join small groups to work on special math problems, based on their previous activities at the Math Forum and their demonstrated skills. Teams of project staff and volunteers will develop Problems of the Week that are specially designed for collaborative learning by these groups. Guided by leading CSCL researchers, project staff will extend Math Forum technology to support the communication and representation needs of the student groups solving these problems collaboratively. Project staff, working with national and international CSCL researchers, will develop and use rigorous, reproducible, practical methods for analyzing the individual and group knowledge building that takes place in the collaborative groups.

3. Project Goal, Objectives, Approach, Prior Work

3.1. Goal

The central goal of the project is to investigate the following working hypothesis:

H0 (collaborative learning hypothesis): A small online group of learners can (on occasion and under favorable conditions) build knowledge and understanding that exceeds that of its individual members.

Although this is an empirical and falsifiable hypothesis, it is unlikely that it will be disconfirmed in this project. A failure to identify instances that confirm this hypothesis within the project data would probably just suggest that the project had not established sufficiently favorable conditions. Rather than trying to either simply confirm or disconfirm this hypothesis, the project aims to clarify the sense in which group knowledge can exceed member knowledge and show concrete cases that illustrate this elusive phenomenon.

3.2. Objectives

In addition to clarifying H0, the project's objective is to determine conditions that are favorable to the construction of group knowledge. These conditions include the composition of the group (H1), the activities the group engages in

(H2), and the technology (software artifacts, communication media) that mediates the collaborative interaction (H3). In particular, to understand how group knowledge can exceed member knowledge, it is important to analyze the relationship of group and individual knowledge and how they can transform into each other (H4). As a critical, reflective research project, the project also aims to specify a research methodology that is consistent with the project findings about the nature of group knowledge (H5). The project therefore studies the following working hypotheses:

H1 (collaborative group hypothesis): Small groups are most effective at building knowledge if members share interests but bring to bear diverse backgrounds and perspectives.

H2 (collaborative curriculum hypothesis): Educational activities can be designed to encourage and structure effective collaborative learning by presenting open-ended problems requiring shared deep understanding.

H3 (collaborative technology hypothesis): Online computer support environments can be designed to facilitate effective collaborative learning that overcomes limitations of face-to-face communication.

H4 (collaborative cognition hypothesis): Members of collaborative small groups can internalize group knowledge as their own individual knowledge and they can externalize it in persistent artifacts.

H5 (collaborative methodology hypothesis): Quantitative and qualitative analysis and interpretation of interaction logs can make visible to researchers the online learning of small groups and individuals.

3.3. Team Approach

The project studying small group collaboration will itself be conducted in a collaborative way, organized into five sets of interacting teams:

T1: Learning Teams: These are the small student groups that will be the primary subjects of the study. They will be groups of 3 to 5 students working together to solve special Math Forum Problems of the Week. Most Learning Teams will be formed online and will work online, generally never meeting each other face-to-face. During the first project year, however, some face-to-face groups of students in local schools will be studied to form a baseline for comparison purposes. Co-PI Weimar will coordinate the recruitment of Learning Team members.

T2: Curriculum Teams: Teams of student teachers, classroom teachers, mathematicians and Math Forum staff will work together to develop special Problems of the Week and associated curriculum for use by the Learning Teams. These Curriculum Teams will also be involved in analyzing the responses to the Problems they develop. Co-PI Bach will coordinate the work of the Curriculum Teams.

T3: Technology Teams: Math Forum technical staff and two project GRAs will work in teams under direct supervision by PI Stahl to design, implement and test collaboration software components. A user-centered design process will be followed, incorporating extensive user testing and iteration throughout the design cycle. Annual week-long workshops for the Curriculum, Cognition and Methodology Teams will provide focused opportunities for teachers and researchers with important experience and expertise to participate in the design process.

T4: Cognition Teams: The national and international researchers will be divided into Cognition Teams and Methodology Teams. The Cognition Teams will be supervised by co-PI Shumar and supported by one project GRA. They will analyze the computer logs of the online groups and any video data or other ethnographic data of the face-to-face Learning Teams.

T5: Methodology Teams: The Methodology Teams, supervised by co-PI Robertson, will assist in the quantitative analysis of data, and will refine and document the research methodology of the project.

3.4. Prior Work on the Math Forum

NSF REC-9155710, Geometry Forum, $1,439,238, June 1992 to November 1996

NSF REC-9554233, Math Forum Pilot, $649,916, October 1995 to September 1997

NSF REC-9618223, Math Forum, $2,922,166, March 1997 to February 29, 2000

NSF REC 9804930, ESCOT, $317,291 (subcontract), October 1998 to September 2001

NSF REC 9805289, BRAP, $293,924 (subcontract), August 1998 to February 2003

NSF DLI-2 9980185, JOMA, $651,948, July 2000 to September 2003

NSF NSDL 0085861, MathDL, $856,257, September 2000 to August 2003

NSF DUE 0127516, Online Mentoring Project, $137,300, February 2002 to January 2004

NSF NSDL 0226284, Math Tools, $853,113, September 2002 to August 2004

The Math Forum is arguably the most widely used math education site on the Internet (search for "math" on Google). It began in January of 1996 as a proof-of-concept grant from the NSF to extend the work of the Geometry Forum into other areas of mathematics and to investigate the viability of a virtual center for mathematics education on the Internet. The Math Forum has developed a vast Web site (mathforum.org) of over a million learning resources and it received more than 650,000 distinct visitors a month (making 2 million visits) in 2001, with mentored user services such as Ask Dr. Math, Problem of the Week, and Teacher2Teacher.

The Math Forum home page allows browsing and searching the Internet Mathematics Library of over 8,600 annotated entries of hand-selected resources. The cataloguing features are based on American Mathematical Society categories, and are enhanced by recommendations of the American Mathematics Metadata Task Force.

The Math Forum's JOMA project (1) searched the Web and other resources to locate and collect applets and similar programs developed by the mathematics research and teaching communities, (2) reviewed and tested these systematically, and (3) made them easily accessible to undergraduate faculty and students. JOMA, *the Journal of Online Mathematics and its Applications,* is published by the Mathematical Association of America. The ESCOT project was a testbed for the integration of innovative technology in middle school mathematics. The Math Forum, working with SRI and other partners, developed team-based approaches that produced math tools for integration into the Problems of the Week. The JOME and ESCOT projects formed the basis for MathDL, an undergraduate-level digital library, a joint project of the MAA and the Math Forum, which is developing the technical infrastructure.

The MathDL and previous projects have given the Math Forum considerable experience constructing libraries and supporting technologies, such as metadata for the NSF digital library initiative. In addition, numerous Math Forum staff members have contributed to NSDL activities, meetings and working groups. The Math Forum was a founding member of the SMETE Open Federation, the largest identifiable user base for the National STEM Education DL.

With TERC and Michigan State University, the Math Forum investigated the possibilities for multimedia articles to open more effective communication between researchers and teachers in a project Bridging Research and Practice. The Math Forum developed a collaborative process through which teachers designed and conducted research into the use of discourse in the math classroom. A video-paper was produced jointly with researchers that served as the focal point for an online conversation with the mathematics education community at large

Currently, the Online Mentoring project is developing a guide to enable professors to integrate online mentoring experiences into their mathematics and mathematics education courses. Pre-service teachers in these courses mentor students submitting their solutions to the Math Forum's Problems of the Week. The results of this project will be used to train mentors for "Technology PoWs," part of a new NSDL funded digital library of mathematics software.

The Math Forum provides many ways for people to interact with one another, with different points of access for people of varied strengths, needs and interests. Community building is an important part of Math Forum activities and has formed the basis of much of the content development on the site. The Math Forum represents a vision about the possibilities for an Internet community that extends the collegiality found in schools, classrooms or the workplace (Renninger & Shumar, 2002b). Evaluation of the Math Forum is used in program design, development, and facilitation, and provides an assessment of impact (Renninger *et al.*, 1989; Renninger & Shumar, 1998).

3.5. Prior Work on Collaborative Learning

NSF CSS IRR-9711951, $725,000, September 1997 – August 2000, "Conceptual Frameworks and Computational Support for Organizational Memories and Organizational Learning (OMOL)," PIs: G. Fischer, G. Stahl, J. Ostwald

NSF EAR 9870934, $89,338, November 1998 – July 1999, "Collaborative Web-Based Tools for Learning to Integrate Scientific Results into Social Policy," PIs: R. Habermann, G. Stahl

European Commission IST-2000-26249, May 2001 – May 2003, "Innovative Technology for Collaborative Learning," Fraunhofer-FIT (including G. Stahl) and researchers in Finland, Spain, Netherlands, Italy and Greece

The CSS grant for the OMOL project was instrumental in the PI's turn from earlier work on organizational memory to support for collaborative learning. The project started from a model of computer support for organizations as domain-oriented design environments in which both domain knowledge and local knowledge are stored in the form of artifact designs and associated design rationale (Fischer *et al.*, 1993). This CSCW model evolved into one of Collaborative Information Environments, that emphasized the interactive, asynchronous, persistent discussion of concepts and issues within an organization (Stahl, 2000a). Gradually, interest in organizational learning aspects led to involvement in CSCL and a model of collaborative knowledge-building environments (Stahl, 2001). A number of software prototypes were developed to explore the use of the Web as a communication and collaboration medium. Of these, the most important for the proposed work was WebGuide (Stahl, 2001), a prototype threaded discussion system that provided multiple perspectives on the discussion, comparison of perspectives and control over rearrangement of notes. Deployment of WebGuide in classrooms raised serious issues of adoption and concerns of socio-technical and social informatics (Kling, 1999) issues: motivation, media competition, critical mass, social practices, seeding, management, re-seeding, convergence of ideas, peer-to-peer collaboration, deployment strategies.

The EAR grant funded the initial implementation of WebGuide as an integrated Java applet supporting personal and group perspectives. It was a joint effort between the PI, a middle school teacher, and a research group at the NOAA labs in Boulder. The teacher taught an environmental science class in which he wanted to spend the year having his students interview various adults and construct a set of contrasting perspectives (conservationist, regulatory, business, community) on a particular local environmental issue that the students had previously been involved in. WebGuide was used by the students to collect notes on their interviews and to formulate personal and team perspectives on the issue. Results of this software trial were analyzed and presented at conferences (Stahl, 1999a, 1999b; Stahl & Herrmann, 1999; Stahl, 2001).

The European Commission grant supported software design and development of BSCL by researchers in Finland, Germany and Spain. The software was implemented as extensions of BSCW, a mature CSCW product used by 200,000 unique users since 1996 (Appelt, 1999). The PI went to work with the BSCW team at Fraunhofer-FIT near Bonn, Germany, for the first year of the project. He prototyped the BSCL innovations and published descriptions of them (Stahl, 2002e, 2003a). During its second year, the project is assessing the use of the new software in schools in Finland, Netherlands, Italy and Greece.

3.6. Our Current Related Work and Related Proposals

Math Forum staff periodically try out mechanisms to support small group collaboration on a small scale. They have provided chat services or encouraged face-to-face groups in classrooms to submit team responses to Problems. These trials generally produce immediate interest from the community, indicating that systematic support for small groups could have dramatic results in stimulating participation in the Math Forum and the associated community.

The PI is exploring small group formation approaches and innovative software functionality to support small group collaboration in his online courses. His students study software support for small group formation, collaborative knowledge negotiation and group use of digital libraries. Each of his HCI courses engages in user studies, software design and user testing of specific applications in these areas.

The PI and co-PIs of this proposal recognize that many research and technical issues related to this project require careful research and technology innovation that go well beyond the scope of the current grant proposal. They have therefore submitted an NSF ITR proposal for innovative technology to form and support collaborative small groups and an NSDL proposal for related research on digital library services to collaborative small groups. Particular co-PIs are also involved in other pending NSF proposals. These related projects – if funded – would be complementary to the project proposed here, but mutually independent. Although co-PI hours might have to be adjusted, there would be different Research Assistants and different goals, objectives and timetables. The present proposal provides the basic research and the necessary evidential basis for the other work. It aims to study in depth the collaborative interactions and the knowledge jointly constructed in collaboratively solving Math Forum problems, using for the project resources and technologies that are almost at hand. Parallel efforts at technology innovation and digital library services in the other projects would allow this study to be refined and significantly extended.

4. Project Plan

4.1. Project Team

The project team consists of five co-PIs (in various schools of Drexel University – see 4.1), collaborating researchers (national and international leaders in CSCL, CSCW and HCI – see 4.2) and members of the Math Forum community (student teachers, classroom teachers, mathematicians and Math Forum staff – see 4.3).

College of Information Science & Technology

Drexel University has a deep interest in and commitment to online collaborative learning. It has large online programs in information science, library science and nursing that use current technologies like Blackboard, WebCT and Lotus Notes and that make extensive use of group learning. Drexel has a long history of computer technology leadership as a former Institute of Technology, including being the first university to require entering undergraduates to have a PC and more recently being judged the "most wired" university according to Yahoo.

Drexel University's College of Information Science and Technology is rated the #1 graduate school of library science information systems by US *News and World Report* (www.usnews.com/usnews/edu/grad/rankings/lib/brief/infsp3_brief.php). This interdisciplinary college offers online and campus-based undergraduate and graduate programs in computer science (e.g., HCI, databases, software engineering) and library science (including digital libraries).

PI Gerry Stahl is an Associate Professor in Drexel University's College of Information Science and Technology. He brings a multidisciplinary background to the project, with PhD dissertations in philosophy/social theory and computer science/AI (Stahl, 1975, 1993b). He has developed a series of collaboration support systems: Hermes (Stahl, 1993a), WebNet (Stahl, 2000a), WebGuide (Stahl, 1999a, 1999b; Stahl & Herrmann, 1999; Stahl, 2001), BSCL (Stahl, 2002e, 2003a), and other educational software: Teachers Curriculum Assistant (Stahl, Sumner, & Owen, 1995; Stahl, Sumner, & Repenning, 1995) and State-the-Essence (Kintsch *et al.*, 2000; Stahl & dePaula, 2001).

Stahl specializes in CSCL research, having published on CSCL theory (Stahl, 1993a, 1998, 2000b, 2002b, 2003b, 2003c) and the use of discourse analysis as an assessment methodology (Stahl & Sanusi, 2001; Stahl, 2002a, 2002c, 2002d). He was Program Chair of CSCL 2002 and Editor of the CSCL 2002 Proceedings (Stahl, 2002f). He is Workshop Chair of CSCL 2003, and Communications Chair and founding Board member of the International Society for the Learning Sciences (ISLS) (isls.org). He teaches online and in-class undergraduate and graduate courses on HCI, CSCL and CSCW at Drexel, using small group collaborative learning methods.

Co-PI Scott Robertson also teaches HCI courses at Drexel's College of Information Science and Technology. Trained in cognitive science, Robertson teaches courses on natural language processing and quantitative research methods as well.

The Math Forum

Co-PI Stephen Weimar has directed the Math Forum since 1994. The Math Forum is now hosted at Drexel University. The Math Forum began in 1992 as the Geometry Forum at Swarthmore College, expanded to the Math Forum in 1996. It was funded in its development by the National Science Foundation, but has become largely self-sustaining in its stable services. It has become one of the most successful applications of the Internet to education through the development of interactive services that bridge the higher education, K-12, and industry communities. These services form the basis for a digital library that generates high quality mathematical content, supports student learning, integrates the benefits of technology with education, and is used for teacher professional development and pre-service teacher education. The Math Forum now comprises over 1.2 million pages of content, has over 2 million visits a month, receives up to 9,000 queries a month at its "Ask Dr. Math" expert service, and mentored over 27,000 students during the 2000-2001 school year through its "Problem of the Week" services. Among its current projects are two NSF grants, one focused on the use of online student mentoring programs in pre-service teacher education courses, and the other on the development of MathTools, a digital library for software in mathematics education from arithmetic to calculus.

Education & Ethnography

Drexel University has a School of Education and a Department of Culture & Communication, both of which are represented in this project. Co-PI Craig Bach is a professor in the School of Education, where he explores the use of technology in education, having developed several hypermedia presentations of topics in mathematics and philosophy. Co-PI Wesley Shumar is a cultural anthropology professor in the Department of Culture & Communication, who specializes in educational anthropology and has conducted ethnographic studies of the Math Forum for many years.

4.2. National and International Collaborators

An important feature of this project is the involvement of leading national and international researchers. They bring expertise from a variety of relevant specialties and perspectives. Their participation will provide a natural means for sharing practical knowledge from Europe and the US as well as for disseminating the results of this project across the nation and globe. To ensure a strong cadre of collaborators, the following researchers have already expressed strong interest in participating in the project; others can join in the future:

The American collaborators are mostly experienced NSF grantees with specialties in particular aspects of CSCL: Geri Gay (Cornell), Ricki Goldman (NJIT), Cindy Hmelo-Silver (Rutgers), Christopher Hoadley (Penn State), Timothy Koschmann (Southern Illinois U), Bonnie Nardi (Irvine), Leysia Palen (Colorado U.), Linda Puliam (California State U.), Mark Schlager (SRI), Dan Suthers (Hawai'i).

The international collaborators are renowned contributors to the theory and practice of CSCL: Wolfgang Appelt (Fraunhofer-FIT, Germany), Thanasis Daradoumis (Barcelona, Spain), Hugo Fuks (Rio, Brazil), Jörg Haake (Distance U, Germany), Kai Hakkarainen (Helsinki, Finland), Thomas Herrmann (Dortmund, Germany), Ulrich Hoppe (Duisburg, Germany), Jim Hewitt (Toronto, Canada), Victor Kaptelinin (Umea, Sweden), Anders Morch (Oslo, Norway), Wolfgang Prinz (Aachen, Germany), Barbara Wasson (Bergen, Norway), Volker Wulf (Siegen, Germany).

These individuals are established leaders in the HCI, CSCW and CSCL research communities, having made important contributions in theory, system design and assessment methodology. They all recognize the importance of collaboration, both in theory and in practice. See the Biographical Sketches section for brief descriptions of each.

The proposed NSF project builds on the work of the European ITCOLE project and its BSCL software (Appelt, 1999; Stahl, 2002e). The PI was the primary designer and prototyper of the BSCL software when he worked at Fraunhofer-FIT in Germany. The project with the Math Forum will involve close collaboration with the BSCW/BSCL team at FIT and has their full support. FIT will continue to support the BSCL code, making it available for free to educational institutions throughout the world. They will also provide training to project staff who will be modifying the BSCL code. FIT has granted a five year developers license to the PI to work on extending BSCL as part of this project. Both Wolfgang Appelt, the BSCW/BSCL team manager, and Wolfgang Prinz, the director of the CSCW department at FIT, personally support the proposed project and its collaboration with FIT (see Supplementary Documentation).

The idea of automated support of group formation for workgroups in online learning is a research topic at the Distance University of Germany (Fern-Uni, Hagen). Jörg Haake, who has begun research on this topic (Haake et al., 2003; Wessner et al., 2002) will be a close collaborator with this project. Several recent publications by the national and international collaborators related to this project are included in the References Cited section (in bold face).

4.3. Management Plan

The PI, Stahl, will have primary responsibility for all aspects of the project. Weimar and Stahl will share project fiscal management, with accounting maintained by the Math Forum and Drexel University. Weimar and Stahl will share project staff management, recognizing that many staff are long-time employees of the Math Forum, contributing part-time.

The project Management Team consists of the five co-PIs, and will meet twice a month.

The project Staff consists of the five PIs, four Math Forum curricular staff, three Math Forum technical staff and three project graduate research assistants:

- G. Stahl, Information Science – Project Manager and Technology Teams Coordinator
- S. Weimar, Math Forum – Learning Teams Coordinator
- C. Bach, Education – Curriculum Teams Coordinator
- W. Shumar, Anthropology – Cognition Teams Coordinator
- S. Robertson, Information Science – Methodology Teams Coordinator
- I. Underwood, Math Forum – Math Forum Ask Dr. Math
- A. Fetter, Math Forum – Math Forum Problem of the Week
- K. Lasher, Math Forum – Math Forum Problem of the Week
- S. Alejandre, Math Forum – Math Forum Problem of the Week
- L. Smith, Math Forum – Math Forum IT director
- D. Tristano, Math Forum – Math Forum software developer
- J. Zhu, Math Forum – Math Forum system administrator
- GRA, Information Science – software developer
- GRA, Information Science – software developer
- GRA, Information Science – ethnography assistant

The project Staff will hold monthly meetings at the Math Forum offices. These meetings will plan detailed project milestones and activities; review progress made according to the milestones; prepare for up-coming activities; review and revise the project plan; and make other decisions about the project as needed. Minutes of these meetings will be posted on the project website with other resources for review by the various teams, acting as project advisors.

Project management will be conducted following a collaborative model, in keeping with the philosophy of the project. Project activities will involve the collaborative teams, with project staff providing staff support and taking responsibility to ensure tasks are accomplished. Each set of teams will be coordinated by a co-PI: Weimar (Learning Teams), Bach (Curriculum Teams), Stahl (Technology Teams), Shumar (Cognition Teams) and Roberson (Methodology Teams). The project is by its nature assessment-centric, evaluating the nature of group learning under different conditions. In addition, the co-PIs will be responsible for various aspects of evaluating the project itself. Shumar will coordinate the experimental design, ethnographic investigation, and formative and summative assessment of the project. While Shumar will focus on qualitative assessment, Robertson will focus on quantitative assessment of project data and of the project itself. Stahl is responsible for coordinating and evaluating the software design and development; Smith for integration of software into the Math Forum site; Weimar for involvement of students and teachers, as well as integration of project activities with other Math Forum activities; and Bach for pedagogical aspects of the project.

Math Forum staff will participate in planning, design and facilitation of the Learner and Curriculum Teams. Math Forum staff will help with logistics, using their existing systems and networks of contacts. They will also help with hosting workshops for the teams as needed. Shumar will coordinate all data collection, and will focus the teams as needed for formative evaluation tasks. Stahl is responsible for project reports, including annual reports to NSF, culling from team summaries. Stahl, Bach, Robertson and Shumar will prepare papers for conferences. Stahl and Weimar will be responsible for dissemination within the NSF and international research communities.

4.4. Infrastructure Technology

This project plans to adapt existing technologies as much as possible and to combine compatible software components into an integrated environment to support collaborative use of the Math Forum by small groups working together on the Internet. Useful components for supporting collaborative communication are available in various configurations and on different programming platforms. The only major component that has to be designed from scratch is a group formation component, and this has largely been worked out in the PI's recent courses. There do not seem to be any group formation components currently available, although the idea is not unprecedented (Swanson, 1964; Twidale & Nichols, 1998). Some organizations have explored systems for locating expertise within their staffs (Ackerman & McDonald, 1996); but the techniques for that do not transfer to the problem of finding people with matching interests using a digital library. There have been some experiments with social awareness, to display other people who are viewing the same web page at the same time (Graether & Prinz, 2001), but this hint is not enough to support group formation. A "group formation" project in Japan matched learning theories (Inaba et al., 2000; Supnithi et al., 1999), but not people. A prototype for group formation in Germany allowed students who knew each other to self-select groups (Haake, Schuemmer, & Haake, 2003; Wessner & Pfister, 2001; Wessner, Dawabi, & Haake, 2002), but this approach does not scale to groups who do not know each other personally. A spin-off of this German research is being expanded and developed for distance education; the project will collaborate with Jörg Haake and associates through the Technology Teams (see section on International Collaboration). It will also collaborate with H. Ulrich Hoppe and Bonnie Nardi, who have both prominently argued for supporting small group collaboration for tasks like digital library search (Hoppe & Zhao, 1994; Nardi & O'Day, 1996).

The PI began exploring support for group formation while teaching an online HCI (Human-Computer Interaction) course for graduate students at Drexel. His students studied the issue and came up with several low-fidelity prototypes that they subjected to user testing. The PI developed an automated grouping agent, which he used to form work groups in subsequent courses. In both the student prototypes and the grouping agent, groups were formed based on specific criteria about the participants: their schedules, their interests and their skill levels. These pilot studies for the proposed project suggest the kinds of balance that should be sought in forming distributed groups. For instance, if synchronous communication is to be possible within the group – especially given different global time zones – members must have compatible schedules. On the other hand, collaborative teams often work best when there is a diversity of perspectives and skills, along with a commonality of interests. Thus, a matching algorithm must optimize certain similarities and other differences. Various theories of collaboration stress the power of heterogeneity, of the utility of seeing things differently: cognitive dissonance (Festinger, 1957), perspectives (Boland & Tenkasi, 1995; Goldnam-Segall, 1998; Stahl & Herrmann, 1999), interdependence (Johnson & Johnson, 1989), zone of proximal development (Vygotsky, 1930/1978), cognitive flexibility (Feltovich et al., 1996).

The PI has informally explored support for small groups in his classes using two different online collaboration environments: Blackboard and BSCL. Blackboard is a commercial system to support collaboration. It is used widely in university courses, particularly in the US. Blackboard can be extended (in Java) by third party developers using the Blackboard Building Blocks SDK (see buildingblocks.blackboard.com/bin/bbdn_info.pl).

BSCL (Basic System for Collaborative Learning) is a system with collaboration support for classrooms that is similar to Blackboard (Stahl, 2002d). It was designed and developed by the PI and others in 2001/2002 as part of a European Union research project. BSCL is an extension (developed in Python) to BSCW (Appelt & Klöckner, 1999), a shared repository CSCW system widely used in European research and learning organizations. It is available for free to academic organizations. The PI has a license to develop it during the period of this project (see Letter of Support in Supplementary Documentation).

The Math Forum already has an infrastructure of custom software (developed in an object-oriented Perl-based environment) to support the virtual community and digital library of math resources and activities. It is possible to extend this system in various directions, such as using ZOPE or other Open Source components, extending Blackboard or adapting features of BSCL. Java applets can also be developed, adapting from the PI's WebGuide system. The project will select one of these approaches during its early phases.

4.5. Timeline

The three year project period is planned to be September 1, 2004 – August 31, 2007. Roughly, work during these years will be focused as follows, based on Drexel University's quarter calendar:

quarter	Learning Teams	Curriculum Teams	Technology Teams	Cognition & Methodology Teams
1. Fall 2004	Recruit teachers	Select appropriate existing PoWs	Hire 2 GRAs	Hire GRA; workshop after CSCW '04
2. Winter 2005	Start up F2F groups	Workshop for teachers	Review existing CSCL technology	Propose method
3. Spring 2005	Observe 3 F2F groups	Define curriculum approach	Study MF technology	Select log segments
4. Summer 2005	Observe 3 more F2F groups	Design 6 new PoWs	Study BSCL technology	Workshop after CSCL '05
5. Fall 2005	Form online groups	Design 6 new PoWs	Study Blackboard technology	Interpret 3 logs
6. Winter 2006	Start collaborative PoWs	Workshop for teachers	User requirements	Analyze cognition in logs
7. Spring 2006	Observe 5 online groups	Study student solutions	Software version 1	Prepare 1 paper
8. Summer 2006	Change group criteria	Re-design curriculum approach	User testing	Workshop after ICLS '06
9. Fall 2006	Observe 5 more online groups	Select 12 new PoWs	Release version 1	Revise method
10. Winter 2006	Observe 3 longitudinal groups	Workshop for teachers	Revise version 2	Interpret 5 logs
11. Spring 2007	Release group formation support	Write teaching manual	Release version 2	Analyze cognition in logs
12. Summer 2007	Review group formation results	Organize digital library of PoWs	Document software	3 papers & handbook

4.6. Project Artifacts

The project will produce a number of concrete artifacts to make the knowledge gained by the project team persistent and available to others:

Evidentiary Base of Interpreted Logs. The Cognition Teams will produce a set of at least eight interpreted logs, illustrating the analysis of group knowledge building.

Math Forum Small Group Services. The project will produce an on-going service at the Math Forum (MF), supporting collaborative knowledge building in Learning Teams with appropriate Problems of the Week (PoWs).

Group Formation Criteria. The project will produce a published set of group formation criteria for the formation of effective Learning Teams.

Problems of the Week for Collaborative Learning. The Curriculum Teams will produce a digital library of Problems of the Week and associated curriculum appropriate for small group collaboration.

Collaboration Technology Design. The Technology Teams will produce designs and documentation for software components to support small group collaboration at the Math Forum.

Theory of Collaborative Knowledge Building. The Cognition Teams will produce at least three conference or journal papers drawing implications from the project for the theory of collaborative learning.

Methodology Handbook. The Methodology Teams will produce a methodology handbook documenting the approach they developed to the analysis of group and individual learning from computer logs of collaborative interactions.

4.7. Project Evaluation

The project as a whole will be considered successful if it achieves the goals and objectives stated in Section 3. That is, if it clarifies what it means to claim that the knowledge of a group can exceed that of its members and if it sheds light on the conditions that favor such collaborative learning. In more specific and measurable terms, the project will be considered successful if it keeps up with the milestones for each set of teams listed in 4.5 above and produces the set of artifacts described in 4.6. In addition, project staff will produce required NSF project reports and participate in associated NSF events.

By its design, the project incorporates in project activities the dissemination of training, research insights and practical tools:

- involving many students, graduate students, student teachers, teachers and researchers;
- integrating research with the educational practices of the Math Forum;
- developing academic papers and practical handbooks

Evaluation is a way of life for most members of the project team. The PI and co-PIs specialize in HCI, ethnography and education – fields that emphasize evaluation of various kinds; Math Forum staff have participated in many NSF grant programs in which evaluation played a central role; the group of national and international researchers includes renowned experts in qualitative and quantitative evaluation.

Evaluation is central to the project. The main project activity is the evaluation of learning – at both the group and individual unit of analysis (H0). There will also be evaluation of the effect of different conditions on this learning, including group composition (H1), curricular activities (H2) and collaboration technology (H3). At a more detailed level, the forms of interplay between the group and individual learning will be evaluated, partially in terms of internalization and externalization processes (H4). This will lead to evaluation and refinement of the project's evaluation methodology itself (H5). Following is an overview of the plan for these evaluation foci, subject to iterative revision as a result of on-going project results:

H0: During the first year of the project, 6 face-to-face groups will be observed working on Math Forum Problems of the Week collaboratively. Observations will take place in local school classrooms affiliated with the Math Forum and Drexel's School of Education, using digital videotaping and ethnographic observation. The primary analysis tool will be discourse analysis, but other techniques will be used to help define the individual and group learning (Fischer & Granoo, 1995). In these cases it will be possible to use pre- and post-tests of individual and group understanding, as well as talk-aloud protocols in individual sessions. This will provide the researchers with a baseline analysis of the relationship of individual and group knowledge. During the second and third years, at least 5 online groups will be studied each year. Of these, students from 3 groups will be observed longitudinally across a series of problems. The longitudinal data will be analyzed to see persistence of knowledge at the individual and group units. The longitudinal data will also shed light on issues of leadership, motivation and interest. Data from the online groups will consist primarily of computer logs of their interactions. There will also be questionnaires about their backgrounds prior to group formation. In a limited number of cases there will be pre- and post-tests of mathematical understanding and personal interviews. Again for the online groups, the primary analysis tool will be discourse analysis of logs. A project GRA will collect, and log all interaction data, with a brief description of each minute of discussion. Interactions will be coded, using a variation of the coding schemes developed by our collaborators (Hakkarainen & Lipponen, 2002; Hmelo-Silver, 2004). The logs and coding will help researchers to locate important interactions for the evaluation of learning at the group and individual unit. Several cases will be selected for intensive discourse analysis to determine if there is plausible evidence that the group knowledge and understanding exceeded that of the individual group members and to determine how that took place – e.g., by the generative power of partially understood words or the merging of perspectives.

H1: Different algorithms for matching students in small groups will be experimentally manipulated in both face-to-face and online Learning Teams. The research literature indicates both that diversity of perspective increases the power of collaboration and that commonality of grounding is necessary. By varying the mix of participants and assessing their success as measured by their problem solutions and their displayed depth of group understanding, the project will evaluate this tradeoff and seek an optimal balance. This working hypothesis is based on rules of thumb from face-to-face collaboration as well as the PI's experience with online problem-based courses; online interaction differs from face-to-face in manifold subtle ways, requiring careful empirical study. Evaluation of success will combine measures of success in group process, quality of knowledge building and depth of understanding as reflected in logs and problem solution (Daradounis *et al.*, 2003; Hakkarainen & Lipponen, 2002).

H2: The Math Forum has extensive experience and success in developing problems at different grade levels and in different areas of mathematics for solution by individuals. In this project, such problems will be adapted for small group collaboration. These collaborative problems may have to be more complex, involve more deep comprehension of mathematical principles, require the use of tools or representations and take longer than a week to discuss and solve. The development of a library of such problems will be challenging and will require both trial-and-error and careful evaluation of how Learning Teams actually do with them. Problems will be rated by the quality of collaborative interaction, the depth of math discussion that they generate, and other standard Math Forum criteria.

H3: There are a variety of CSCL software components available for incorporation or adaptation to this project. The Technology Teams will evaluate the applicability of these to the Math Forum context in the first year. Then they will specify, design, implement and test iterative versions of support for the Learning Teams. The software will be carefully evaluated for its fit in this particular, concrete educational practice, using HCI evaluation methods and analysis of communication and collaboration breakdowns in the logs.

H4: Interactions that were found under the H0 evaluation to indicate group knowledge exceeding member knowledge will then be interpreted through further discourse analysis to determine the extent to which group knowledge was either internalized by certain individuals or externalized in the group report.

H5: The ability of the project to accomplish the evaluations associated with H0 and H4 in particular will reflect the extent to which H5 is confirmed. As with H0, it is not so much a matter of verifying or falsifying the hypothesis as it is of the Methodology Teams of researchers refining the use of discourse analysis of computer logs to make visible the group and individual knowing that was expressed in the online interactions.

5. Anticipated Results & Impact

5.1. Dissemination & Outcomes

Dissemination of project results, both in the US and in Europe, is built into the project design. Dissemination to the international research community, to practicing educators and to the public generally will take place primarily through the following mechanisms:

Involvement of international researchers. Approximately two dozen researchers will be intimately involved in this project, primarily through the Cognition Teams and Methodology Teams. Many of their graduate students will also be involved. Most of these researchers are active in important research centers.

Workshops at international conferences. The project will sponsor one workshop per year to bring together international and American researchers collaborating with the project. This may be coordinated with international conferences on education such as CSCL, ICLS, CSCW, ECSCW, AERA and EARLI. Most of the researchers involved in this project regularly attend these conferences and present at them. These conferences will be primary sites for the presentation of results from this project. Project staff will also submit papers and organize presentations about the project results at these conferences.

Involvement of teachers and student teachers. Perhaps two dozen teachers and student teachers will be intimately involved in this project, primarily through the Curriculum Teams. As the results of this project become part of Math Forum's regular services, increasing numbers of teachers and student teachers will participate in spontaneously formed curricular workgroups. The project will bring Curriculum Team members together in intensive week-long workshops each year.

The Math Forum virtual community. This is a rapidly growing community that already numbers over a million distinct individuals. They will learn about the results of this project as collaborative problems become a regular feature of the Math Forum and as community participants are automatically invited to join small groups for collaborative learning of mathematics.

The NSF community. Project findings will be presented at NSF gatherings where Math Forum or project participants are involved.

5.2. Sustainability & Contribution

The results of this project, particularly the collaborative Problem of the Week service, will be fully incorporated in the Math Forum. The Math Forum is a permanent program within Drexel University, so that services developed in this project will continue to exist and to be used indefinitely. Although the Math Forum receives grants to engage in research and service expansion, it strives to develop revenue sources to sustain existing services. The collaboration services of this project will contribute to building new lines of revenue, including contracted services with school districts for which Math Forum will provide custom collaboration services and support.

5.3. Integration of Research & Education

The project itself integrates research and education. It provides empirical support for the design and development of resources and services to support math education over a broad range of school grades, as well as for meeting educational needs of employees, mathematicians and lifelong learners. It does this from a position situated in the practical work of the Math Forum. The specific content of this project applies technologies at the forefront of CSCL and CSCW research directly to educational practice. By implementing collaborative learning services in an established educational context, the project studies actual instances of the practice it hopes to foster.

5.4. Integrating Diversity

A central project hypothesis is that groups integrating specific kinds of diversity learn better. Project software will be designed to optimize diversity during the group formation process. The online environment removes many of the barriers to collaboration among people with differences in age, knowledge, gender, culture, physical abilities, geographic location. The project will demonstrate the creative power of diversity takes in collaboration.

5.5. Intellectual Merit

This project addresses straight-on a central hypothesis of CSCL that has never been adequately clarified and documented. It seeks to develop an evidentiary basis for a controversial assumption common in learning theories today: that group knowledge can be something distinct from the sum or overlap of the individual knowledge of the group members. This assumption lies at the center of much of the current debate and confusion in educational theory, yet little in the way of clear and incontrovertible empirical examples have been presented before now. This project studies the building of group knowledge in the context of extending the services of one of the most successful online educational institutions, simultaneously studying issues of group composition, curriculum design, technology support and assessment methodology. To accomplish this, the project brings together five co-PIs with the required mix of expertise, along with teams of engaged educators and researchers.

5.6. Broader Impacts

The project develops rigorous methods for studying the online construction of group knowledge. By overcoming the paradigm conflict concerning collaborative learning, the project reconciles basic research and educational practice and provides a research base for CSCL and for virtual learning communities like the Math Forum user community. It develops technical, social and pedagogical mechanisms to bring diverse individuals together to learn, and offers a model, support tools and a research base for collaborative educational services. It does this with the help of leading national and international educational researchers, promoting in-depth collaboration at this level as well. These are all contributions to realizing the potential of Internet technology to not only make human knowledge accessible to everyone, but to promote collaborative knowledge building on a global scale.