Gerry Stahl's assembled texts volume #11

Essays in Philosophy of Group Cognition

Gerry Stahl

Gerry Stahl's Assembled Texts

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Essays in Philosophy of Group Cognition

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Introduction

Essays in Philosophy of Group Cognition (vol. 11) presents my philosophical writings from the end of my career (mostly published around 2016) and from during retirement (published 2021). So, it complements *Essays in Social Philosophy* (vol. 7), which covers my early thinking (originally published 1967-1989).

The essays in this volume seek to address foundational questions related to the concept of *group cognition*. This concept emerged in the writing of my first book, *Group Cognition* (Stahl, 2006a), where the theoretical themes of the present volume were already discussed (mainly in Part III, especially Chapter 16). The idea that small teams of students could engage in productive group cognition in settings of Computer-Supported Collaborative Learning (CSCL) was proposed as a tentative hypothesis, requiring investigation. Particularly the possibility of collaborative problem solving in mathematics was largely a hope, which motivated an extended research project.

I directed the Virtual Math Teams (VMT) project (2002-2016) to explore the potential of collaborative learning of mathematics, taking advantage of computer support to bring together small groups of students to problem solve, learn and think together. The project's goal was to develop collaboration software, draft guiding curriculum, run trials with groups of students in realistic conditions, collect detailed data on their interaction and analyze what took place. The project adopted a highly iterative "design-based research" approach, through which theory of group cognition emerged from cycles of trial, analysis and re-design.

Empirical studies of group cognition in the VMT project involving problems of combinatorics common in middle-school math courses were presented in *Studying Virtual Math Teams* (Stahl, 2009), where Part IV focused on conceptualizing group cognition in VMT. When the VMT project switched to dynamic geometry as its mathematical domain, *Translating Euclid* (Stahl, 2013) included Chapter 8 on theory, sketching a theory of referential resources and offering reflections on shared understanding. At the end of the VMT Project, *Constructing Dynamic Triangles Together* (Stahl, 2016a) provided a detailed longitudinal case study oriented toward the adoption of group practices as providing preconditions for group cognition. It confirmed that group cognition could occur in CSCL settings and could be traced through discourse analysis showing the adoption of group practices.

The research of the VMT Project investigated and documented instances of small-group interaction that displayed group cognition in mathematical problem solving. It thereby confirmed the hypothesis proposed in *Group Cognition*. This research integrated technology design, curriculum development, realistic trials, systematic analysis of interaction and theory development. These aspects of the project were discussed in numerous conference presentations, journal articles and book chapters.

The present volume includes a selection of the most important essays that address the philosophical issues raised in those broader publications. A discussion of philosophy of group cognition should tackle the following questions:

- What is the nature of group cognition?
- What conditions make group cognition possible?

Question (a) seeks a definition or description of group cognition: What are its characteristics and how does it differ from (or relate to) other forms of cognition, such as individual cognition and social cognition? Question (b) inquires about what the necessary preconditions are that allow group cognition to take place, such as shared understanding among the group members.

The title of this collection is slightly awkward. It is about "philosophy of group cognition," rather than "the philosophy" or "a philosophy." It makes no pretentions to being the only possible analysis of its topic, nor to being a complete system. On the other hand, it does not position itself as one among many alternative philosophies. Rather, it offers a collection of essays that complement each other by refining the answers to questions (a) and (b) from different perspectives and based upon excerpts of empirical student data.

Essays are not systematic presentations, but are arguments addressed to specific audiences. Each of the essays in this compilation was intended to explain the notion of group cognition to a different audience. Each was also formulated at a specific point during the trajectory of the VMT research project. By contrast, this compilation of complementary essays is not addressed to a special audience. It is for anyone interested in thinking about the foundational questions of group-cognition theory.

This volume consists of essays previously published as book chapters and journal articles. An early version compiled in 2015 collected 14 chapters spanning the period of the VMT Project. After I retired, I decided to republish new versions of these chapters in the Springer CSCL book series as *Theoretical Investigations* (Stahl, 2021d), along with my favorite theoretical articles from the *International Journal of Computer-Supported Collaborative* learning (*ijCSCL*), which I edited from 2006-2015.

In 2021, I revised the contents of the present self-published volume. I included new philosophical or theoretical essays that I have written during retirement. I also incorporated the introductory essays from *Theoretical Investigations* and retained several of the most important chapters from there, so they would be easily available for a larger audience. The included essays are described below.

As it turned out, the essays originally published in this volume were not my last writings on the philosophy of group cognition. Rather, these increasingly theoretical works led to further reflections that extended them significantly, most importantly in

Theoretical Investigations (Stahl, 2021d). This book not only reprinted selected papers on CSCL theory from *ijCSCL* and from my own papers, but included two new chapters: "Investigation 1, Advancing a CSCL Vision" (Stahl, 2021a) and "Investigation 2, A Theory of Group Cognition in CSCL" (Stahl, 2021b).

In addition, I co-authored two chapters of the *Handbook of CSCL* (Cress, Rosé, Wise & Oshima, 2021): "Theories of CSCL" (Stahl & Hakkarainen, 2021) and "Analysis of Group Practices" (Medina & Stahl, 2021).

The book of *Investigations* is included in my eLibrary as volume 19. Its two introductory chapters and the two *Handbook* chapters are included in this volume. They expand greatly on the initial insight reported in the chapter of this book on "Practices in Group Cognition" (Stahl, 2017).

This volume begins with a recently revised version of "An Historical Introduction to CSCL" (Stahl, Koschmann & Suthers, 2006), a popular intro to CSCL from the perspective of group cognition.

1. Introduction to CSCL

The present volume opens with a new version of what is probably the most cited publication in the research field of Computer-Supported Collaborative Learning (CSCL), originally entitled "An Historical Introduction to CSCL" (Stahl, Koschmann & Suthers, 2006). It appeared in *The Handbook of the Learning Sciences*, edited by Keith Sawyer in 2006. It was a collaboration with Tim Koschmann and Dan Suthers, two friends and colleagues who deeply influenced my view of CSCL. For the 2021 third edition of the *Handbook*, we revised the text to focus more decisively on what is most definitive of CSCL, the collaborative nature of knowledge building. We felt this was still important because the theory of CSCL is not well understood or universally agreed to. The original version of the chapter appears in Volume 15 of my assembled texts, accompanied by translations into Spanish, Portuguese, German, Romanian and Chinese, both Traditional and Simplified.

2. Theories of CSCL

This chapter (Stahl & Hakkarainen, 2021) of the *CSCL Handbook* compiled for Springer's CSCL book series was co-authored with Kai Hakkarainen, a leading researcher of CSCL in Finland and Professor of Psychology. It was a particularly fruitful collaboration as we were both interested in pushing the field of CSCL to more centrally incorporate some of the recent theoretical trends in the social sciences. Kai led major EU research projects incorporating Activity Theory. I worked with Kai in 2002/03, when I was in Europe.

3. Analysis of CSCL

The other *Handbook* chapter (Medina & Stahl, 2021) was a collaboration with Richard Medina, who I had met at Dan Suthers' lab in Hawaii. Richard is an ethnomethodologist whose dissertation analyzed data from my VMT project. He had thought deeply about the issues of analyzing this kind of interactional data, so he was able to contribute much of the detailed material on steps of analysis, as well as partnering on the conception of the chapter overall.

4. Curriculum for CSCL

This essay (Stahl, 2021c) was inspired by the global coronavirus pandemic, which abruptly forced much education to take place online, when almost no one was ready for implementing CSCL. I tried to show how the approach explored in VMT could be adopted as a model for adapting curriculum to blended modes of learning and instruction. It is related to my illustrative curriculum, *Dynamic Geometry Game for Pods* (vol. 21 of my eLibrary publications).

5. Technological Artifacts

I include a philosophic essay (Stahl, 2021e) on music because it represents my most detailed reflection on the nature of technological artifacts. I reproduce the text as written for a philosophy book on Heidegger and music, without trying to adapt it more explicitly to the context of CSCL and group cognition. I think it shows how the world of things comes to have the nature that it does through a complex interaction of people, physicality, history, culture and usage.

The version included here is an extended version of what was published. It includes an added closing section critiquing Heidegger's conception of social history, returning to the problematic of my 1975 philosophy dissertation and providing *my best conclusion thereto*. It also offers a far clearer articulation of my first philosophy article – on electronic music (1976). The published version is reproduced in volume 7, which includes my early writings on philosophy and on music.

6. Introducing Theoretical Investigations

Here is the brief opening of *Theoretical Investigations* (Stahl, 2021d). It situates the following two involved discussions.

7. A Vision of Group Cognition

Investigation 1 presents considerations of my vision of group cognition as a powerful intellectual force in the world of the future through an overview of the dozen articles reprinted in *Theoretical Investigations* from the *International Journal of CSCL*, which I founded and edited for its first decade.

8. The Theory of Group Cognition

Investigation 2 then discusses my own 11 theoretical papers that are included in *Theoretical Investigations*, of which 7 are pre-printed in the present volume. It also incorporates several *ijCSCL* editorials that I wrote over the years to encourage theoretical discourse in the CSCL research community.

9. A Post-cognitive Theoretical Paradigm

This essay reflects on the relationship of the research fields of CSCL and the Learning Sciences. It takes a historical view from an autobiographical engaged perspective, arguing that a new paradigm of CSCL based on group cognition can provide a theoretical basis for the learning sciences. It was published as a chapter in a volume on the history of the learning sciences, (Stahl, 2016c). It sketches a context for understanding the potential centrality of group cognition within a new research paradigm.

10. Practices in Group Cognition

The next essay (Stahl, 2017) was the first "squib" in *ijCSCL*, a brief article presenting a controversial new approach to the field. It characterizes (a) the nature of group cognition using the concept of "group practice," as developed at the end of the VMT Project. It summarizes the finding of the role of group practices in *Constructing Dynamic Triangles Together* (Stahl, 2016a), and argues that the analysis of group practices provides a new method for analysis in design-based research approaches to CSCL. It references several of the following chapters for the theoretical framework of an approach to CSCL focused on the identification of group practices.

11. Co-experiencing a Virtual World

This essay summarizes three doctoral dissertations on student interaction in the VMT Project. It points to the establishment within a virtual math team of a shared world as the precondition of effective group cognition. The essay was published as (Stahl, Zhou, Çakir & Sarmiento-Klapper, 2011). It provides a further glimpse of the themes of this volume, grounded in earlier VMT case studies of student interaction in problem-solving groups.

12. From Intersubjectivity to Group Cognition

In twentieth-century philosophy, the term "intersubjectivity" has generally raised the issue of how group cognition is possible: how can the ideas or utterances of one person be understood by other people? The journal of CSCW wanted commentaries to a lead article on "we-awareness." This paper (Stahl, 2016b) was submitted as one of the commentaries. It took the opportunity of this occasion to review the most important statements about intersubjectivity by philosophers and social scientists.

13. Constituting Group Cognition

This essay (Stahl, 2014) was written for an edited book on philosophies of embodied cognition. Group cognition took its place there next to other contemporary philosophical approaches to understanding how people think and act in the world. It addressed the issue of how group cognition is constituted in the discourse of a small group.

14. Sustaining Group Cognition

Group cognition—such as the collaborative solving of a challenging mathematics problem—takes place through discourse and inscription. The analysis of the discourse is undertaken with a version of conversation analysis, adapted to student teams discussing math rather than informal adult conversation. An important adaptation is to consider longer sequences of back-and-forth than simple conversation pairs. The analysis in this chapter (Stahl, 2006b) uncovers a group's sustained discourse effort at problem saving, in which the group completes the kind of problem solving that is often accomplished by individuals.

15. Structuring Group Cognition

Going beyond the analysis of longer discourse sequences, my keynote address (Stahl, 2011) to a conference in Hong Kong displays the hierarchical structure of group cognition in a typical CSCL session, involving analytical levels of the event, sessions, themes, discourse moves, adjacency pairs, utterances and references. It thereby proposes a structure for analyzing the data collected in VMT sessions.

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Contents

1. Introduction to CSCL

Gerry Stahl, Timothy Koschmann, Dan Suthers

The vision of Computer-Supported Collaborative Learning (CSCL) transforms common approaches to online education, harnessing the power of collaboration and identifying the requirements for achieving its potentials. When this chapter was revised in 2020, the Coronavirus pandemic had rendered the makeover of educational practice urgent worldwide. Suddenly, teachers, students, parents and politicians realized that online learning was necessary, but that few people knew how to make it pedagogically effective. The research field of CSCL has been researching the complex and intertwined issues involved in this for many years. CSCL proposes a set of responses to realize the possibilities of online learning while recognizing the multiple areas requiring innovative approaches for this vision to be achieved.

During the pandemic, teachers turned to communication technologies like Zoom, to course organizers like Blackboard, to information sites like Wikipedia and to social media apps like Twitter. People assumed that teachers could continue to provide instruction in traditional ways through these digital media. However, none of these applications were designed to support learning. Communication media were devised for business meetings, course management systems were to administer classrooms, online info services provide de-contextual facts and social media exchange personal opinions. In contrast, CSCL aims to support collaboration that builds beyond individual ideas and isolated facts to create shared knowledge.

The goal of CSCL can be described using multiple terminologies, stemming from different disciplinary traditions. This chapter discusses CSCL in terms of each of these conceptualizations:

- *Collaborative knowledge building*: constructing knowledge artifacts like scientific theories by groups of students building on each other's contributions.
- *Dialogic interaction*: merging ideas by discussion from different people's perspectives.
- *Intersubjective meaning making:* developing shared sense of topics through discourse, including emotion and gesture.
- *Group cognition*: allowing knowledge to emerge in group processes, rather than just in individual minds.

CSCL is a field of study that necessarily combines multiple disciplines. Because it is "computer supported," it involves digital technology. However, no application is a CSCL tool by itself. It must be appropriately adopted by its users within a CSCL context. For instance, there needs to be an established culture of collaborative learning, i.e., a set of CSCL pedagogy practices. To achieve this, the technology must be designed in accordance with CSCL theories, which describe how collaborative learning takes place. Technologies need to be developed within iterative cycles of realistic trials with students to analyze how the hardware and software are actually used to build group knowledge. Accordingly, CSCL is a multi-faceted effort, integrating:

- *Theory*: understandings of the nature of group-level processes involved in achieving effective collaborative learning.
- *Methodology*: ways to analyze the intersubjective meaning making that takes place in small-group dialogical interaction.
- *Pedagogy*: educational approaches to establish group practices that de-emphasize individual competition in favor of collaborative knowledge building.
- *Technology*: artifacts designed to promote group cognition and demonstrated to foster desirable group practices.

CSCL is an innovative conceptualization and implementation of learning and thinking. It takes advantage of technological opportunities for increased networking of students as well as increased support by informational and computational resources. Not all learning should be CSCL style; teachers should design CSCL sessions and orchestrate them into well-designed sequences of individual, group and classroom learning. CSCL represents a significant departure from teacher-centered and individual-student-focused learning, which offers complementary forms of learning. The sections of this chapter explain the CSCL paradigm in four stages:

- How CSCL is a visionary approach to education.
- How CSCL technology, analysis, pedagogy and theory emerged over 25 years.
- How CSCL presents an innovative approach to online learning.
- How CSCL can develop in the future.

CSCL Within Education

As the study of certain forms of learning, CSCL is intimately concerned with education. It considers all levels of formal education from kindergarten through graduate study, as well as informal education, such as museums. Computer technology has become important at all levels of education, with school districts and politicians around the world setting goals of increasing student access to computers and the Internet. Importantly, computer networks can bring students together across time and space to collaborate —both asynchronously and in real time, remotely and face-to-face. The idea of encouraging students to learn together in small groups has also become increasingly emphasized in the Learning Sciences, as seen in many chapters of this *Handbook*. However, the ability to combine these two ideas (computer support and collaborative learning, or technology and education) to effectively enhance learning remains a challenge—a challenge that CSCL is designed to address.

Computers and Education

Computers in the classroom are often viewed with skepticism. Critics see them as boring and anti-social, a haven for geeks, and a mechanical, inhumane form of training. CSCL is based on precisely the opposite vision: it proposes the development of new software and applications that bring learners together to offer creative activities of intellectual exploration and social interaction.

CSCL arose in the 1990s in reaction against software that forced students to learn as isolated individuals. The exciting potential of the Internet to connect people in innovative ways provided a stimulus for CSCL research. As CSCL developed, unforeseen barriers to designing, disseminating and effectively taking advantage of innovative educational software became increasingly apparent. A transformation of the whole concept of learning was required, including significant changes in schooling, teaching and being a student. Many of the necessary changes are reflected in the educational approaches presented in Part 1 of this *Handbook*, for instance adopting educational frameworks such as knowledge building (Scardamalia & Bereiter, Chapter 18, this volume), scaffolding (Reiser & Tabak, Chapter 3, this volume) or situativity (Engeström & Greeno, Chapter 7, this volume).

Online Learning at a Distance

CSCL is often conflated with online learning, the organization of instruction across computer networks. Online learning is too often motivated by a naïve belief that classroom content can be digitized and disseminated to large numbers of students with little continuing involvement of teachers or other costs, such as buildings and transportation. There are several problems with this view.

First, it is simply not true that the posting of content, such as slides, texts or videos, makes for compelling instruction. Such content may supply important resources for students—just as textbooks always have—but they can only be effective within a larger motivational and interactive social context.

Second, online teaching requires at least as much effort by human teachers as classroom teaching. Not only must the teacher prepare materials and make them available by computer, but the teacher must also motivate and guide each student, through on-going interaction and a sense of social presence. While online teaching allows students from around the world to participate and allows teachers to work from any place with Internet connectivity, it has generally been found to significantly increase teacher effort per student.

Third, CSCL stresses collaboration among students, so that they are not simply reacting in isolation to posted materials. The learning is done by groups, through interaction among students. Student groups learn collaboratively: by expressing questions, pursuing lines of inquiry together, teaching each other and seeing how others are learning. Computer support for such collaboration is central to a CSCL approach to online learning. Stimulating and sustaining productive student interaction is difficult to achieve; it requires skillful planning, coordination and implementation of curriculum, pedagogy and technology. It presupposes the establishment of a culture of collaboration in classrooms, as opposed to competition (e.g., testing and grading).

Fourth, CSCL is also concerned with face-to-face (F2F) collaboration. Computer support of collaborative learning does not always take place through an online communication medium; the computer support may involve the construction and exploration of a computer simulation of a scientific model or a shared interactive representation. Alternatively, a group of students might use a computer to browse through information on the Internet and to discuss, debate, gather and present what they found collaboratively. Computer support can take the form of distant or F2F interaction, either synchronously or asynchronously.

Cooperative Learning in Groups

The study of group learning began long before CSCL. Since at least the 1960s—before the advent of networked personal computers—there was considerable investigation of cooperative learning by education researchers (Enyedy & Stevens, this volume).

To distinguish CSCL from this earlier investigation of group learning, it is useful to draw a distinction between *cooperative* and *collaborative* learning. In a detailed discussion of this distinction, Dillenbourg (1999) defined the distinction roughly as follows:

> In cooperation, partners split the work, solve sub-tasks individually and then assemble the partial results into the final output. In collaboration, partners do the work "together." (p. 8)

He offered as an example Roschelle & Teasley's (1995) description of collaboration in which a form of social learning is accomplished using a computer as a cognitive tool:

> We investigate a particularly important kind of social activity, the *collaborative construction of new problem-solving knowledge*. Collaboration is a process by which individuals *negotiate and share meanings* relevant to the problem-solving task at hand…. Collaboration is a coordinated, synchronous activity that is the

> result of a continued attempt to construct and maintain a *shared conception* of a problem. (p. 70, emphasis added)

In *cooperation*, the learning is done by individuals, who then contribute their individual results and present the collection of individual results as their group product. Learning in cooperative groups is viewed as something that takes place individually—and can therefore be studied with the traditional conceptualizations and methods of educational and psychological research.

By contrast, in the Roschelle and Teasley characterization of *collaboration*, learning occurs socially as the collaborative construction of knowledge. Of course, individuals are involved in this as members of the group, but the activities that they engage in are not primarily individual-learning activities, but group interactions like negotiation and sharing. The participants do not go off to do things individually but remain engaged with a shared task that is constructed and maintained by and for the group as such. The collaborative negotiation and social sharing of *group meanings*—phenomena central to collaboration—involve a *socio*-logic. We call this *meaning making*. It is the group as a whole that conducts the problem solving, shares new meaning, and builds knowledge or group practices. Understandings built in collaboration rest upon epistemological assumptions that are different from those typically employed in educational research and call for a different set of research methods.

Collaboration and Individual Learning

As we have just seen, collaborative learning involves individuals as group members, but also involves group phenomena like the negotiation and sharing of meanings—including the construction and maintenance of shared conceptions of tasks—that are carried out interactively in group processes. Collaborative learning involves individual learning but is not reducible to it (see Nathan & Sawyer, this volume). The relationship between viewing collaborative learning as a group process versus as an aggregation of individual change is a tension at the heart of CSCL.

Earlier studies of learning in groups treated learning as a fundamentally individual process. The fact that the individuals worked in groups was treated as a contextual variable that influenced the individual learning. In CSCL, by contrast, learning is also studied as a group process; research on learning at both the individual and the group unit of analysis is necessary. This is what makes CSCL methodologically unique, as we shall see later in this chapter.

CSCL developed in reaction to earlier attempts to use technology within education and to previous approaches to understand collaborative phenomena with traditional methods. The Learning Sciences have shifted from a narrow focus on individual learning to an incorporation of individual, group and community learning—and the evolution of CSCL has paralleled this movement.

The Historical Emergence of CSCL

From Conferences to a Global Community

In 1983, a workshop on the topic of "joint problem solving and microcomputers" was held in San Diego. Six years later, a NATO-sponsored workshop was held in Maratea, Italy. The 1989 Maratea workshop was the first public and international gathering to use the term "computer-supported collaborative learning" in its title.

The first full-fledged CSCL conference was organized at Indiana University in the fall of 1995. Subsequent international meetings have taken place biennially. The CSCL conference proceedings have been a primary vehicle for publications in the field. Several journals have also played a role, including the *Journal of the Learning Sciences* and the *International Journal of Computer-Supported Collaborative Learning,* which started publishing in 2006. A CSCL book series published by Springer began then also.

From Artificial Intelligence to Collaboration Support

The field of CSCL can be contrasted with earlier approaches to using computers in education. Koschmann (1996) identified the following historical sequence of approaches: (a) computer-assisted instruction, (b) intelligent tutoring systems, (c) programming, (d) CSCL.

(a) Computer-assisted instruction was a behaviorist approach that dominated the early years of educational computer applications beginning in the 1960s. It conceived of learning as the memorization of facts. Domains of knowledge were broken down into elemental facts that were presented to students in a logical sequence through computerized drill and practice. Many commercial educational software products still take this approach.

(b) Intelligent tutoring systems—based on a cognitivist philosophy—analyzed student learning in terms of mental models and potentially faulty mental representations. They rejected the behaviorist view that learning could be supported without concern for how students represented and processed knowledge. Considered particularly promising in the 1970s, this approach created computer models of student understanding and then developed software that responded to student actions based on occurrences of typical errors found in models of student problem solving. Intelligent tutoring systems are a prime example of AI, because they replicate the actions of a human tutor. This is still an active research area within the learning sciences (see Koedinger, this volume), but is limited to domains of knowledge where mental models can be algorithmically defined. It was natural that computer scientists interested in educational applications of computer technology would be attracted by the exciting promises of artificial intelligence (AI); researchers in AI and Education were influential in CSCL.

(c) The third use of computers in education began in the 1980s; it was epitomized by the teaching of the Logo programming language—as a training ground for logical thinking (Koschmann, 1997). Logo programming took a constructivist approach, arguing that students must build their knowledge themselves. It provided stimulating environments for students to explore and to discover the power of reasoning, as illustrated in software programming constructs like functions, subroutines, loops, variables or recursion.

(d) CSCL represents the most recent use of computers in education. CSCL approaches explore how computers can bring students together to learn collaboratively in small groups and in learning communities. Motivated by social-constructivist and dialogical theories, these efforts provide and support opportunities for students to learn together by directed discourse that constructs shared knowledge.

Within CSCL, the focus is on learning through collaboration with other students rather than directly from the teacher. Therefore, the role of the computer shifts from supplying instruction—either in the form of facts in computer-aided instruction or in the form of feedback from intelligent tutoring systems—to supporting collaboration by providing media of communication and scaffolding for productive student interaction.

The primary form of collaboration support is for a network of computers to provide a medium of communication. This may take the form of email, chat, discussion forums, videoconferencing, instant messaging, etc. CSCL systems typically offer a combination of several media and add special functionality to them.

Since the early days of CSCL, social media have become widely available and heavily used by students. They often offer media of communication for CSCL, but they are problematic. Commercially designed for non-educational applications, apps like Facebook and Twitter foster distraction, limited time on task and sharing of trivia, preconceptions, gossip, flaming, emotion, fake news, culture wars and stubborn personal opinions. They are not designed to support rich collaborative knowledge building, scientific investigation or the construction of insightful shared meaning. They lack the discipline-specific supports of CSCL systems, which may include teacher guidance, relevant background knowledge, exploratory models, learning scaffolds, extended time-on-task or reflection and feedback components.

CSCL software environments provide various forms of pedagogical support for collaboration processes. These may be implemented with computational mechanisms, including AI techniques. They can offer alternative views on the ongoing student discussion and emerging shared information. They can supply feedback, possibly based on a model of group inquiry. They can encourage sociability by monitoring interaction patterns and offering contextualized information to students. In most cases, the role of the computer is secondary to the interpersonal collaboration process among the students (often guided by a teacher, tutor or mentor). The software is designed to support, not replace or distract from, these group processes.

The shift from mental models of individual cognition to support for collaborating groups had enormous implications for both the focus and the method of research on learning. The gradual acceptance and unfolding of these implications have defined the evolution of the field of CSCL.

From Individuals to Interacting Groups

At about the time of the first CSCL conference in 1995, Dillenbourg, et al. (1996) analyzed the state of evolution of research on collaborative learning as follows:

> For many years, theories of collaborative learning tended to focus on how *individuals* function in a group. This reflected a position that was dominant both in cognitive psychology and in artificial intelligence in the 1970s and early 1980s, where cognition was seen as a product of individual information processors, and where the context of social interaction was seen more as a background for individual activity than as a focus of research. More recently, *the group itself has become the unit of analysis* and the focus has shifted to more emergent, socially constructed, *properties of the interaction*.
>
> In terms of empirical research, the initial goal was to establish whether and under what circumstances collaborative learning was more effective than learning alone. Researchers controlled several independent variables (size of the group, composition of the group, nature of the task, communication media and so on). However, these variables interacted with one another in a way that made it almost impossible to establish causal links between the conditions and the effects of collaboration. Hence, empirical studies have more recently started to focus less on *establishing parameters for effective collaboration* and more on trying to *understand the role that such variables play in mediating interaction*. This shift to a more process-oriented account requires *new tools for analyzing and modeling interactions*. (p. 189, emphasis added)

The research reviewed by Dillenbourg et al.—which studied the effects of manipulating collaboration variables on the measures of individual learning—did not produce clear results. Effects of gender or group composition (i.e., heterogeneous or homogeneous competence levels) might be completely different at different ages, in different domains, with different teachers, and so on. This not only violated methodological assumptions of variable independence but raised questions about how to understand what was behind the effects. To get behind the effects meant to understand in some detail what was going on in the group interactions that might cause the effects. This, in turn, required the development of methodologies for capturing, analyzing and interpreting group interactions as such. The focus was no longer on what might be taking place "in the heads" of individual learners, but what was taking place between them in their temporal interactions (Enyedy & Stevens, this volume).

From Mental Representations to Interactional Meaning Making

The shift to studying processes at the group unit of analysis coincided with a focus on the community as the agent of situated learning (Engeström & Greeno, this volume; Lave, 1991) or collaborative knowledge building (Scardamalia & Bereiter, 1991; this volume). But it also called for the elaboration of a social theory of mind, such as Vygotsky (1930/1978) had begun to outline, which could clarify the relation of individual learners to collaborative learning in groups or communities.

According to Vygotsky, individual learners have different developmental capabilities in collaborative situations than when they are working alone. His concept of the "zone of proximal development" is defined as a measure of the difference between these two capabilities. This means that one cannot measure the learning—even the individual learning—that takes place in collaborative situations with the use of pre- and post-tests that measure capabilities of the individuals when they are working alone. To get at what takes place during collaborative learning, it does not help to consider what may be in the heads of individuals, because that does not capture the processes of *shared meaning making* that are going on within collaborative interactions.

Collaboration is primarily conceptualized as an activity of shared meaning construction. Meaning is not treated as an expression of mental representations of individual participants, but as an interactional achievement of the group. Meaning making can be analyzed as taking place across sequences of utterances or messages from multiple participants. The meaning is not attributable to individual utterances of individual students because the meaning typically depends upon indexical references to the shared situation, elliptical references to previous utterances and projective preferences for future utterances.

From Quantitative Comparisons to Micro Case Studies

To view learning in collaborative situations is different from observing it for isolated learners. First, in situations of collaboration, participants necessarily visibly display their learning as part of the process of collaboration. Second, the observations take place across short periods of group interaction, rather than across longer periods between pre- and post-tests.

Ironically, it is in principle easier to study learning in groups than in individuals. That is because a necessary feature of collaboration is that the participants display for each other their understanding of the meaning that is being constructed in the interaction. Utterances, texts and diagrams that are produced during collaboration are structured by the participants to display their understanding. That is the basis for successful collaboration. Researchers can take advantage of these displays (if they share the participants' interpretive competencies and can capture an adequate record of the displays, e.g., on digital video). Researchers can then reconstruct the collaborative process through which group participants constructed shared meaning and adopted group practices.

Methodologies like conversation analysis (Sacks, 1992) or video analysis (Koschmann, Stahl & Zemel, 2005) based on ethnomethodology (Garfinkel, 1967) produce detailed case studies of collaborative meaning making (Chinn & Sherin, this volume; Enyedy & Stevens, this volume). These case studies are not merely anecdotal. They can be based on rigorous scientific procedures with intersubjective validity even though they are interpretive in nature and are not quantitative. They can also represent generally applicable results, in that the methods that people use to interact are widely shared (within appropriately defined communities or cultures).

How can the analysis of interactional methods help to guide the design of CSCL technologies and pedagogies? This question points to the complex interplay between education and computers in CSCL.

The Interplay of Learning and Technology in CSCL

Emerging New Conceptions of Learning

In the past, educational researchers treated learning as a purely psychological phenomenon. Learning was taken to have three essential features: First, it represents a response to and recording of experience. Second, learning is treated as a change that occurs over time. Finally, learning is seen as a process not available to direct inspection (Koschmann, 2002). This formulation is so culturally entrenched that it is difficult to conceive of learning in any other way. It rests upon established traditions in epistemology and philosophy of mind.

Edwin Thorndike (1912), a founder of the traditional educational approach, wrote:

> If, by a miracle of mechanical ingenuity, a book could be so arranged that only to him who had done what was directed on page one would [page] two become visible, and so on, much that now requires personal instruction could be managed by [automated] print. (p. 165)

This quotation is notable in that it suggests that the central idea of computer-aided instruction long preceded the actual development of computers. More importantly, it also shows how the goal of research in educational technology is closely tied, indeed indistinguishable from, the conventional goal of educational research, namely, to enhance learning as operationally defined. Thorndike envisioned an educational science in which all learning is measurable and, on this basis, by which all educational innovations could be experimentally evaluated (Jonçich, 1968; Koschmann, 2011). Historically, research on educational technology has been tied to this tradition and represents a specialization within it (Cuban, 1986).

CSCL stands apart from more conventional approaches to doing educational research not only in terms of the types of technologies and instructional methods that it uses, but more fundamentally in its epistemological philosophy (theory of how knowledge is possible and what knowledge consists of). Research in education has traditionally rested upon a "Correspondence Theory of Truth." Knowledge, in this regard, consists of inventories of facts—propositions that are true by virtue of their observable correspondence to a fixed reality regardless of circumstances (David, 2016). Learning, under such an epistemological theory, entails the acquisition of true propositions. Embracing this view, Thorndike held that the first task for an educational science was to design reliable instruments for assessing a subject's knowledge, conceived of as acquired facts and propositions (Jonçich, 1968).

In situations of conjoint activity, such as collaborative learning, a different treatment of knowledge comes into play. Knowledge under these circumstances is not context-independent—just the opposite. What counts as knowledge is worked out within interaction between parties and is inextricably bound to the setting and circumstances in which they find themselves. What is taken to be known is evaluated in terms of mutual understanding and situational coherence. For this reason, philosophers refer to this as a "Coherence Theory of Truth" (Young, 2018). Rather than acquiring an inventory of decontextualized facts, collaborative learning under such a theory is a witnessable process of sense making or knowledge building by the group in the moment. To study sense making in the moment not only requires a different conceptualization of learning, but also a different set of methods than those employed previously in educational research.

Building on this view, the so-called "edifying philosophers" (Rorty, 1974)—James, Dewey, Wittgenstein and Heidegger—rejected the view of learning as an inaccessible event in which knowledge is inscribed in individual minds. CSCL—focused on collaborative learning—embraces this situated view of learning, thereby rejecting the tenets of traditional educational research. CSCL locates learning in meaning negotiation carried out in the social world rather than in individuals' heads. Of the various socially oriented theories of learning, social practice theory (Lave & Wenger, 1991; Reckwitz, 2002) and dialogical theories of learning (e.g., Hicks, 1996; Wegerif, 2006) most directly subscribe to a view of learning as socially organized meaning construction. Social practice theory focuses on one aspect of meaning negotiation: the negotiation of social identity and knowledge within a community. Dialogical theories locate learning in the emergent development of meaning within social interaction. Taken together, they offer a new way of thinking about and studying learning.

Designing Technology to Support Group Meaning Making

The goal for design in CSCL is to create artifacts, activities and environments that enhance the practices of group-meaning making. Rapid advances in computer and communication technologies in recent decades have dramatically changed the ways we work, play, think, discuss and learn. No form of technology, however, no matter how cleverly designed or sophisticated, has the ability, by itself, to change practice. To create the possibility of an enhanced form of practice requires multifaceted forms of design, bringing in expertise, theories and practices from various disciplines: to address curriculum (pedagogical and didactic design), resources (information sciences, communication sciences), participation structures (interaction design), tools (design studies) and surrounding space (architecture).

As the title of a commentary by LeBaron (2002) suggests, "Technology does not exist independent of its use." Substitute "activities, artifacts and environments" for "technology" and the message remains the same—these elements by themselves cannot define new forms of practice but are instead constituted within practice. An environment for a desired form of educational practice becomes such through the organized actions of its inhabitants. Tools and artifacts are only tools and artifacts in terms of how they are oriented to and made relevant by participants in directed practice. Even activities are only rendered recognizable as such by how participants orient to them as ordered forms of joint action.

Design of software for CSCL, therefore, must be coupled with analysis of the meanings constructed within emergent practice. Meanings reflect past experience and are open to endless negotiation and re-evaluation. Group participants routinely engage in coordinated activity and operate as if shared understanding was both possible and continually being achieved. A fundamental question, therefore, is: How is this *intersubjective* meaning making accomplished? To design technology to support collaborative learning and knowledge building, we must understand in more detail how small groups of learners construct *shared* meaning using various artifacts and media.

The question of how *intersubjectivity* is established and maintained has been taken up in a variety of specialized disciplines such as pragmatics (Sperber & Wilson, 1982), social psychology (Rommetveit, 1974), linguistic anthropology (Hanks, 1996), philosophy (Stahl, 2021, Investigation 18) and sociology (cf. Goffman, 1974), especially sociological research in the ethnomethodological tradition (Garfinkel, 1967; Heritage, 1984). The problem of intersubjectivity is particularly of relevance for those who wish to understand how learning is produced within interaction. Learning can be construed as the act of bringing divergent meanings into contact (Hicks, 1996), and instruction as the social and material arrangements that foster such negotiation. The analysis of meaning making calls for the appropriation of the methods and concerns of psychology (especially the discursive and cultural varieties), sociology (especially the micro-sociological and ethnomethodologically informed traditions), anthropology (including linguistic anthropology and anthropologies of the built environment), pragmatics, communication studies, organizational science and others.

CSCL research has both analytic and design components. Ethnomethodological analysis of meaning making is inductive and indifferent to reform goals. It seeks only to discover what people are doing in moment-to-moment interaction, without prescription or assessment. Technological design, on the other hand, is inherently prescriptive—any effort toward reform begins from the presumption that there are better and worse ways of doing things. To design for improved meaning making, however, requires some means of rigorously studying practices of meaning making. In this way, the relationship between analysis and design is a symbiotic one—design must be informed by analysis, but analysis also depends on design in its orientation to the desired group practices (Koschmann et al., 2005; Stahl, 2016).

CSCL must continue with its work of self-invention: introducing new sources of theory, presenting analyses of learner practice and designing technological artifacts guided by theories of how they might enhance meaning making. The design of CSCL technology, which opens new possibilities for collaborative learning, must be founded on an analysis of the nature of collaborative learning.

The Analysis of Collaborative Learning

Koschmann (2002) presented a programmatic description of CSCL in his keynote at the 2002 CSCL conference:

> CSCL is a field of study centrally concerned with meaning and the practices of meaning making in the context of joint activity, and the ways in which these practices are mediated through designed artifacts. (p. 18)

The definition of CSCL as being concerned with the "practices of meaning making in the context of joint activity" can be understood in multiple ways. A traditional "cooperative" interpretation would focus on the individual mental efforts of participants in a group, applying social practices to construct their own personal meanings. However, in CSCL, we are concerned with group practices of meaning making, conducted through interactional processes and resulting in shared meanings. Meanings—such as the meanings of words, drawings, gestures, theories—are never fundamentally private; they are essentially forms of communication within groups or cultures and must be mutually understandable.

The aspect of collaborative learning hardest to comprehend is what may be called *intersubjective meaning making* (Suthers, 2006) or *group cognition* (Stahl, 2006; 2009, 2013, 2016, 2021). This is learning that is not merely carried out interactionally but is actually *constituted* out of the interactions between participants. Following Garfinkel, Koschmann et al. (2005) argued for the study of "member's methods" of meaning making: "how participants in such [instructional] settings actually go about *doing* learning." In addition to understanding how the cognitive processes of participants are influenced by social interaction, we need to understand how learning events themselves take place in the interactions between participants.

The study of joint meaning making is not yet pervasive within CSCL research. Even where interaction processes (rather than individual learning outcomes) are examined in detail, the analysis is often undertaken by assigning coding categories and counting pre-defined features. The codes, in effect, substitute preconceived categories of behavior for the phenomenon of interest, rather than seeking to discover and interpret those phenomena in their unique situations (Stahl, 2002). Coding is useful for comparing experimental cases, but not for analyzing sequential interactions.

A few studies published in the CSCL literature have directly addressed this problem of describing the constituting of intersubjectivity in interaction (for example, Koschmann et al., 2003; Koschmann et al., 2005; Roschelle, 1996; Stahl, 2006, 2016). Roschelle's early study designed software to support meaning making related to physics, defined student activities to engage learners in joint problem solving and analyzed their collaborative practices in micro detail. Koschmann's work has generally focused on participants' methods of *problematization*: how groups of students collectively characterize a situation as problematic and as requiring further specific analysis.

Stahl (2006) argued that small groups are the most fruitful unit of study, for several reasons. Most simply, small groups are where members' methods for intersubjective learning can be observed. Groups of several members allow the full range of social interactions to play out but are not so large that participants and researchers alike necessarily lose track of the interactions. The shared construction of meaning is most visible and available for research at the small-group unit of analysis, where it appears as *group cognition*. Moreover, small groups lie at the boundary of, and mediate between, individuals and their communities. The knowledge building that takes place within small groups becomes "internalized by their members as individual learning and externalized in their communities as certifiable knowledge" (Stahl, 2006, p. 16). Small groups may learn by adopting social practices as their own group practices and then potentially appropriating them as individual skills of the group participants (Stahl, 2016).

Small groups should not be the only social granularity studied within CSCL. Analysis of large-scale changes in communities and organizations may lead to an understanding of emergent social-learning phenomena as well as elucidate the role of embedded groups in driving these changes. It is important to research the intertwining of processes on the individual, small-group and community levels of analysis.

The study of the interactional accomplishment of intersubjective meaning making or group cognition gives rise to interesting questions that are among the most challenging facing any social-behavioral science, and even touch upon our nature as conscious beings: How do cognitive phenomena take place trans-personally in group discourse? How is it possible for learning, traditionally conceived of as an individual cognitive function, to be distributed across people and artifacts? How can we understand knowledge as accomplished practice rather than as a mental substance or even as an individual's predisposition? The perspective of CSCL on these matters requires overcoming engrained ways of thinking about cognition in terms of individual minds.

The Analysis of Computer Support

In typical CSCL contexts, interactions among individuals are mediated by computer environments. The second half of Koschmann's programmatic definition of the domain of CSCL involves "the ways in which these practices [meaning making in the context of joint activity] are mediated through designed artifacts" (Koschmann, 2002, p. 18). Computer support for intersubjective meaning making is what makes the field unique.

The technology side of the CSCL agenda focuses on the design and study of fundamentally social technologies. This means that the technology is designed specifically to mediate and encourage social acts that constitute group learning and may subsequently lead to individual learning. Design should leverage the unique opportunities provided by the technology rather than replicate support for learning that could be done through other means, or (worse) try to force the technology to do something for which it is not well suited. What characteristics of information technology can facilitate effective CSCL?

- Computational media can be reconfigurable. Representations are dynamic: it is possible to move things around and undo actions. It is easy to replicate those actions elsewhere: one can bridge time and space. These features make information technology attractive as a "communication channel," but we should exploit technology for its potential to make new interactions possible, not simply force it to replicate face-to-face interaction.

- Computational media can "turn communication into substance" (Dillenbourg, 2005). A record of activity, as well as digital products can be retained, replayed and repeatedly modified. We should explore the potential of the persistent record of interaction and collaboration as a resource (group memory) for intersubjective meaning making.

- Computational media can analyze the workspace state and interaction sequences they support. They can reconfigure themselves or generate prompts according to what takes place in the media. We should explore the potential of adaptive media as an influence on the course of intersubjective processes, and take advantage of their ability to prompt, analyze and selectively respond. Computational media supporting student groups can inform teachers in real time about how each group is progressing (learning analytics: Baker & Siemens, this volume).

Human communication and the use of representational resources for this communication is highly flexible: we cannot "fix" meanings or even specify communicative functions (Dwyer & Suthers, 2006). Informed by this fact, CSCL research should identify the unique advantages of computational media and explore how collaborators use these and how they influence the course of their meaning making. This would enable the design of technologies that offer collections of features through which groups can interactionally engage in learning with flexible forms of guidance.

The Multidisciplinarity of CSCL

Research in CSCL to date has generally followed three methodological traditions: (a) experimental studies, (b) descriptive case studies and (c) the design of new ways of instructing, some projects drawing on more than one approach.

(a) Following in a tradition which can be traced back to Thorndike (Koschmann, 2011, p. 6), many CSCL studies are set up as clinical trials in which an intervention is compared to a control condition in terms of one or more variables. Scores are generated using a measurement instrument or a coding procedure of some sort. These can then be pooled to control for individual variability and permit the making of statistical inferences. Such methods can be used to evaluate the effectiveness of the intervention, i.e., whether it works. This leaves, however, other questions open, such as, how the intervention is actually accomplished in any particular context and what meaning does the instructional activity hold for the participants.

(b) Studying how meaning is established intersubjectively in the moment, one must look beyond simple scores to the practical settings from which the scores were extracted. This entails using more descriptive and ethnographic methods borrowed from the social sciences (Koschmann, 2018). One cannot make generalized claims based on a case study, but such studies can provide useful insight into how an intervention works. Indeed, such situated studies may enable us to discover what the intervention is!

The foregoing considerations might suggest that we explore hybrid (Johnson & Onwuegbuzie, 2004) or multi-vocal (Suthers, et al., 2013) research methodologies. Experimental designs can continue to compare interventions, but the comparisons would be made in terms of micro-analyses of how the features of information technology influence and are appropriated for members' methods of joint meaning making. Conceptually, the process analysis changes from "coding and counting" to "exploring and understanding" ways in which design variables influence support for meaning making. Such analyses are time intensive: we should explore, as research aids, the development of instrumentation for learning environments and automated visualization and querying of interaction logs (as in Cakir et al., 2005; Donmez et al., 2005).

Traditional analyses, especially measures of learning outcomes but also "coding and counting," might also be retained to obtain quick indicators of where more detailed analyses are merited, thereby focusing the detail work (as in Zemel, Xhafa & Stahl, 2005). When blending methods from different traditions, however, researchers must be mindful of possible differences in epistemological assumptions that are built into these traditions.

(c) Beyond the questions of whether collaborative learning works and how learning in settings of collaboration is accomplished is the question: How can we make collaborative learning *better*? Design has been central to CSCL research from the very beginning of the field. In our sister field of CSCW, the question of precisely how ethnographically based empirical research can inform design of technologies has been discussed at length (e.g., Button, Crabtree, Rouncefield & Tolmie, 2015). Design-Based Research (DBR) has been advanced as the primary means of accomplishing this in the Learning Sciences (see Barab, this volume). DBR draws upon the *iterative design* tradition. Driven by the dialectic between theory and informal observations while engaging stakeholders in the process, design-oriented researchers continuously improve artifacts intended to mediate learning and collaboration in cycles of design, testing, analysis and redesign. It is not enough to just observe people's behaviors when they use new software. We need to explore the space of possible designs, pushing into new areas and identifying promising features that should receive further study. While the results of prior experimental research may provide clues for initial design and clinical trials may be important to eventual evaluation of an innovation, iterative examination of the innovation-in-use is an essential component of DBR (Koschmann, Stahl & Zemel, 2005). This is because ethnographic and descriptive methods are most applicable to understanding how meaning-making is accomplished in the augmented learning situation.

A potential limitation of both experimental and descriptive methodologies should be noted. If we focus on finding examples of how members accomplish effective learning, we may miss examples of how they also fail to do so. To find that something is not there, we need to have an idea of what we are looking for. Common patterns found in successful learning episodes subsequently become the theoretical categories we look for elsewhere with analytic methods, and perhaps fail to find in instances of unsuccessful collaboration. Having identified where the successful methods were *not* applied, we can then examine the situation to determine what contingency was missing or responsible.

Unique and un-reproducible instances where collaboration using technology breaks down in interesting ways can often provide the deepest insights into what is happening, and into what is normally taken for granted and invisible.

CSCL Research in the Future

Research in CSCL responds to multiple goals and constraints. The research community includes people from a variety of professional and disciplinary backgrounds and training. They bring with them different research paradigms, contrasting views of data, analysis methods, presentation formats, concepts of rigor and technical vocabularies. They come from around the world with various cultures and native languages. CSCL is a rapidly evolving field, located at the intersection of other fields (like the learning sciences generally) that are themselves undergoing continuous change. Community participants at any given time are operating within diverse conceptions of what CSCL is all about.

Sfard (1998) defined two broad and irreconcilable metaphors of learning that are necessarily relevant to CSCL: the acquisition metaphor, in which learning consists of individuals acquiring knowledge stored in their minds, and the participation metaphor, in which learning consists of increasing participation in communities of practice. Koschmann (2001) suggested that a third metaphor for learning could be found in Dewey's notion of transactional inquiry (Dewey & Bentley, 1991). For Dewey, inquiry becomes transactional when it considers the phenomenon under investigation, not detached from its environment, but rather in its full interconnectedness. Applying this idea to learning would require us to recognize that learning results in more than just a change to the individual, but is rather a transaction between that individual and the social and material environment in which that individual is situated, through which both are changed. Lipponen et al. (2004) proposed another candidate for a third metaphor based on Bereiter (2002) and Engeström (1987): the knowledge-creation metaphor, in which new knowledge objects or group practices are created in the world through collaboration. Both proposals gesture in the direction of a new treatment of learning, one built upon a different epistemology and one calling for a new set of research methods.

Research methodology in CSCL is largely trichotomized between experimental, descriptive and iterative design approaches. Although sometimes combined within a single research project, the methodologies are even then typically kept separate in companion studies or separate analyses of a single study. Different researchers sometimes wear different hats on the same project, representing different research interests and methodologies. It is always important that researchers clearly identify the approach they are using, including its consistent theoretical and methodological framework.

A multi-vocal approach may be productive despite its tensions (Suthers, et al., 2013): the experimentalists may identify variables that affect general parameters of collaborative behavior; the ethnomethodologists may identify patterns of joint activity that are essential to meaning making; and designers may innovate to creatively adapt new technological possibilities. Experimentalists within CSCL may start to focus on the dependent variables that directly reflect the phenomena of interest to descriptive researchers (Fischer & Granoo, 1995); more ethnographically-oriented researchers, on the other hand, may look for *predictive* regularities in technology-mediated meaning making that can inform design; and designers may generate and assess promising new technology affordances in terms of the meaning-making activities or "group practices" (Stahl, 2016) they enable. Mutual assistance and closer collaboration may be possible through hybrid methodologies, for example by applying richer descriptive analytic methods to the problem of understanding the implications of experimental manipulations and new designs, or through computer support for our own meaning-making activities as researchers.

CSCL researchers form a community of inquiry that is actively constructing new ways to collaborate in the design, analysis and implementation of computer support for collaborative learning. A broad range of research methods from the learning sciences may be useful in analyzing CSCL, supported by corresponding theoretical conceptualizations.

Having appropriated ideas, methods and functionality from cognate fields, the CSCL community may now construct new theories, methodologies and technologies specific to the task of analyzing group practices and intersubjective meaning making to support collaborative learning (Medina & Stahl, 2021; Stahl, 2021; Stahl & Hakkarainen 2021).

We have argued here that CSCL requires a focus on the meaning-making practices of collaborating groups and on the design of technological artifacts to mediate group interaction, rather than a primary concern with individual learning. While multiple theories, pedagogies, technologies and analysis methods may be necessary in response to the complexity of CSCL, we believe that those that are oriented to and focused on the intersubjective meaning making at the center of collaborative learning are particularly appropriate to CSCL research and practice, and set CSCL apart from the rest of the Learning Sciences.

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2. Theories of CSCL

Gerry Stahl and Kai Hakkarainen

Abstract. This chapter examines collaborative learning as cognition at the small-group unit of analysis, and highlights theoretical questions concerning interrelationships among individual, collective and cultural cognition. CSCL is a theory- and research-based pedagogical vision of what collaborative learning could be like, thanks to innovative computational supports and new ways of thinking about learning. Theories of CSCL are shaped by rapidly evolving digital technologies, pedagogical practices and research methods. Relevant theories can be categorized as: subjective (individual cognition and learning), intersubjective (interactional meaning making) and inter-objective (networks of learners, tools, artifacts and practices). Theoretical insights suggest ways of enhancing, supporting and analyzing cognition and learning by individuals, groups and communities. The emerging ecology of socio-digital participation—involving students' daily use of computers, mobile devices, social media and the Internet—requires extending and synthesizing CSCL theories to conceptualize connected learning at multiple levels.

Introduction & Scope: Theory of Theories

Educational research and practice should be informed by theory. However, CSCL has adopted and spawned a variety of competing theories. How should CSCL researchers and practitioners react to the current situation and what should they expect in the future?

Theories of CSCL are important to define what is unique about CSCL and to counter misunderstandings about the nature and aims of CSCL as an evolving research field. CSCL is a theory- and research-based pedagogical vision of what collaborative learning could be like, given the development of innovative computational supports and new ways of conceptualizing knowledge (epistemology), thought (cognition) and (collaborative) learning—largely influenced by contemporary and emerging philosophical approaches and theories. Hence, CSCL is not simply the study of the use of existing technologies in conventional educational settings, as analyzed by traditional methods and theories. Rather, new theories have implications for designing CSCL technologies, associated pedagogic practices and analytic methods.

To examine the role of theory, we need to examine the question of just what "*CSCL*" is.

Some treat it as simply a form of educational technology, where students communicate over networked devices, possibly enhanced through some AI application. From this perspective CSCL can involve learning either "through" or "around" CSCL technology (Lehtinen et al., 1999). The former involves CSCL environments mediating—or providing a medium for—learners' synchronous or asynchronous online interaction, whereas the latter engages learners interacting face-to-face and co-creating knowledge or artifacts around digital devices, such as models, drawings, art works or craft objects developed on computers or tablets. Technological development is, however, blurring boundaries of such activities, as all knowledge work increasingly involves socio-digital technologies.

Others define CSCL in distinction to "cooperative" learning, where tasks are divided among students in a group working on a task, whereas collaborative learning involves joint pursuit of knowledge objects (Knorr-Cetina, 2001), which learners seek to understand by co-authoring texts or other products incorporating evolving shared meaning and common understanding. CSCL is also contrasted with Computer-Supported Cooperative *Work* (CSCW), where adults work together on professional tasks using computer support.

Still others focus on the intersubjective aspects of collaboration, which involve real-time interaction in small groups and associated efforts of meaning making. Post-humanist approaches highlight the active role of digital and other artifacts and physical, virtual or mixed environments in which enacted collaborative activity is embedded. Such an "inter-objective" (Latour, 1996) framework guides one to examine how multiple people learn as a group, community or network by building joint meaning and constructing shared artifacts within technologically rich environments.

This chapter will review the changing role of theory in CSCL, the major theories that are currently influential in the field, as well as their philosophical and methodological underpinnings. This chapter's discussion of theories of CSCL is anchored to an examination of interrelations and mutual shaping among the technologies, practices and research methods of CSCL (Figure 1), characterized as follows.

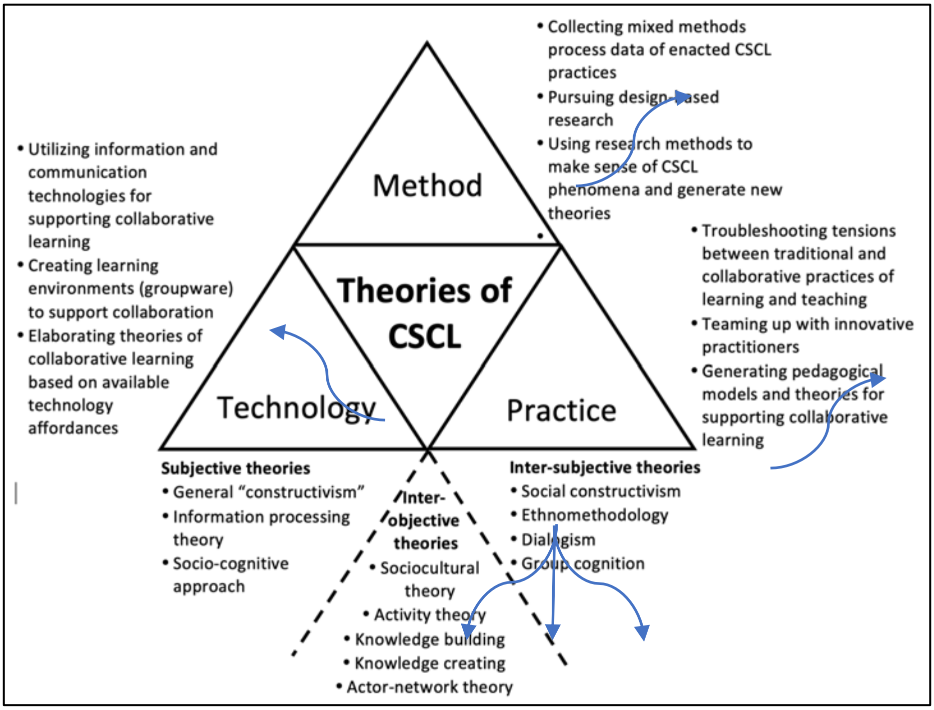

Figure 1. Framework for examining theories of CSCL.

- *Technology:* The emergence of the CSCL field was associated with the development of information and communication technologies or groupware systems that enabled synchronous and asynchronous interaction and collaboration among learners. These developments inspired environments and theories for collaborative learning. The future of CSCL will continue to be mediated by rapid development of socio-digital technologies. However, the use of generic social media apps is in tension with CSCL's traditional focus on specialized applications for collaboration. Commercially developed social media (like FaceBook or Twitter) are predominantly designed for exchange of personal opinions (resulting in flaming and fake news) rather than for supporting intersubjective processes of knowledge building in domains like argumentation, sciences and mathematics.

- *Practice*: Educational use of CSCL technologies is a systemic endeavor anchored in social practices of students, teachers and educational institutions. The impacts of CSCL technologies are mediated both by prevailing educational practices and enacted practices of using these technologies in learning and instruction. CSCL investigators have developed pedagogic frameworks and guidelines for supporting innovative CSCL implementations, together with developing theories for understanding practices of CSCL and its transformative dynamics. The socio-political agenda of CSCL to improve the quality of learning, democratize knowledge and promote educational equity requires CSCL researchers to work closely with educators in iterative design experiments to implement CSCL in context.

- *Method:* With their research methods, investigators analyze CSCL processes and practices, contributing to redesign of CSCL technologies and pedagogic models, as well as refining theories of CSCL. Analyses of CSCL in practice have motivated theories of cognition that is socially and materially distributed, temporally and socially emergent, and embodied, enactive, embedded and extended. The field has developed specific methods and investigative practices for studying collaborative learning at multiple levels: from the individual and small group to classroom/community/cultural/societal units of analysis.

What kind of theory is appropriate and useful for deepening understanding, explanation and advancement of CSCL?

The theory of science has morphed considerably in recent decades (see e.g., Latour & Woolgar, 1979), away from former positivist conceptions of theory and of science. Today, the goal of a theory of CSCL is a controversial moving target, not an established canon of universally accepted principles. We will be less concerned with predictive theory typical for the natural sciences, and more with theory as a tool for understanding and transforming learning and education. A number of theories have been prominent in CSCL during the past 25 years due to the trans-disciplinary nature of the field; researchers trained in specific fields—such as education, design, psychology, computer science, anthropology or linguistics—brought with them theories, methodologies and philosophies of science from these quite diverse enterprises.

This has resulted in a confusing variety of incommensurate, competing theories influential within CSCL research. For instance, the most common theories identified in recent content meta-analyses of CSCL (Akkerman et al., 2007; Jeong & Hmelo-Silver, 2016; Jeong, Hmelo-Silver & Yu, 2014; Kienle & Wessner, 2006; Lonchamp, 2012; Wise & Schwarz, 2017; Tang, Tsai & Lin, 2014) were constructivist, socio-cultural, social-psychological and information-processing frameworks. It is not clear what specific theories correspond to these vague classifications, which are often grouped based on loose author self-identification rather than by looking at the approaches actually applied in the reported research. Difficulties in comprehensively characterizing CSCL theories reflect the complexity of the evolving field, where different research questions require distinct kinds of investigation.

To clarify the range of traditional and emerging theories, we have categorized them under these headings: *subjective* (foregrounding individual cognition and learning), *intersubjective* (centered on interactional meaning making) and *inter-objective* (emphasis on building of heterogeneous networks of learners, tools, artifacts and practices). These overlapping categories of theories have been crucial for understanding the field of CSCL, its developmental history and its envisioned future.

In the following sections, we will suggest elements of a more integrated theory of CSCL. We first review the history of CSCL technologies, practices and methods, as tied to the subjective, intersubjective and inter-objective theories that seem critical for advancement of the field.

History & Development

Interdependence of Theory and Method

Historical shifts in theory both influenced and responded to changes in research practices, analysis methods and focal concerns of CSCL research. The theories influence how researchers define their object of study, how they investigate it and how they interpret their findings.

Much theory in CSCL came from the subjective theories of empirical approaches in psychology—cognitive, educational and social psychology—and contributed assumptions and research methods for CSCL. Although the pioneering contributions of psychologists like Brown (1992) highlighted the importance of pursuing field case-studies in actual classrooms, the psychological sciences generally prioritized controlled laboratory experiments and statistical measures of collected data.

Because implementation of CSCL in education calls for systemic change in social practices that individualistic psychological theories are unable to account for, subjective approaches have been critiqued, complemented, expanded and partially replaced by approaches that emphasize materially and socially distributed aspects of thinking and learning, rather than mental models or symbolic representations. Such development has been critical for the development of CSCL, given its technological and social mediation of learning. One way to understand the history of psychological theories is as a sequence from positivism and behaviorism to cognitivism, and then to socio-cultural theory—or from individual cognition to situated, distributed, group and social cognition. Controlled experiments to measure individual learning gains have been either complemented or replaced with in-depth case studies or longitudinal ethnographies, without which emerging CSCL practices could not have been fully understood, adequately explained or deliberately fostered.

The recognition of the complexity of learning in CSCL settings necessitates extending the theory and bringing in conceptualizations and methods from related fields. Hence, CSCL theories increasingly invoke and adapt methods from other social sciences, including linguistics and anthropology. The resulting contextualized approaches to analyzing cognition address thinking and learning as involving people situated in dialog with others, within a world of language, artifacts and culture. Such CSCL studies often use interaction analysis or design-based research to understand and explore how groups of students interact using technological artifacts and systems. Especially in CSCL, the primary actor, cognitive agent or collaborative learner may be seen as the small group itself (Stahl, 2006). Collaborative learning can be studied at various interdependent units of analysis—such as linguistic moves and embodied actions (e.g., gesturing, sketching and prototyping)—and at different levels of social organization—such as an individual person, team, classroom, community or culture.

Surveys of methodological practices of CSCL often reflect on how theoretical frameworks affect the analysis methods of investigators. However, available technologies and methods can provide access to specific kinds of empirical phenomena and data, in turn inspiring the refinement of CSCL theory. In human sciences, methods and tools can create the very phenomena (research objects) of investigation, so that theories, methods or technologies are interdependent (Gigerenzer, 1994). In the development of the field of CSCL, interventions with discussion forums gave rise to theories of computer-mediated communication; the use of video games resulted in micro-analytic studies of small-group cognition; and studies of collaborative environments, such as Knowledge Forum (Scardamalia, this volume), shaped knowledge-building theories. The recent emergence of digital fabrication technology and educational maker spaces expand the scope of CSCL epistemologically, theoretically and methodologically, to centrally involve the role of materially embodied artifacts in collaboration.

CSCL studies rely on complementary bodies of thick, thin and rich big data (Hillman & Säljö, 2016). They collect *thick data* though ethnographic and participant observations, interviews and documentation of design experiments. Such data is needed for understanding, examining and further refining learners' and teachers' socio-digital knowledge practices. CSCL studies may also utilize *thin data*, i.e., self-report response data that enable tracing learning, motivation and socio-digital activity. Self-report data may be needed for showing the perceived impact of interventions. Moreover, CSCL investigators have developed novel instruments and methods for tracing and analyzing the "big" data of contextual, digitally mediated learning activities and processes. Such big data can be interpreted along with thick process data and thin self-report data. CSCL research addresses complex and often messy efforts of implementing collaborative practices in education and, therefore, often uses mixed methods for reaching robust understanding of CSCL processes. Although design-based and interventionist approaches appear to dominate CSCL, it is also important to continue pursuing controlled experiments for testing the impact of well understood practices of using technology, possibly within the cycles of design-based research.

There is growing recognition that human cognition takes place on multiple, interdependent levels, and that research methods should include approaches at the individual, small group, community and network units of analysis. One could use different methods at each unit of analysis and then identify links between them. A central open question involves how the levels interact. This must become a vital concern of further development of theories of CSCL.

Diversity of Theories & Traditional Oppositions

An important distinction between different theoretical frameworks depends on the focal unit of collaboration.

Subjective theories focus on the individual mind—admitting that student learning is influenced by the social context but measuring the effects of participation in the group on the individual members as psychological subjects.

Inter-objective theories are more oriented to social, community and cultural levels of analysis—emphasizing linguistic interactions or embeddedness of learning on networks of people and artifacts. They are concerned with analyzing and cultivating the social practices in which learning is embedded and the social institutions that structure learning activities. The collaborative group then stands in the middle, between the individuals who participate in the group, tools and artifacts used, and the community or larger network whose practices the group adopts and adapts as it learns collaboratively.

Intersubjective theories focus on the group itself as the unit of analysis. Collaborative learning, which takes place in CSCL primarily at the group unit, can have consequences at the other levels, leading to learning outcomes for the individuals or transformation of community social practices (Lave & Wenger, 1991).

The array of theories has evolved through a series of historical developments. The history of Western philosophy from the early Greeks to the present provides many of our now commonsensical assumptions about scientific method (Stahl, 2020, Investigation 15). Empiricism, for instance, culminated in positivism and its view of objective knowledge. Rationalism assumed that all cognition took place in individual minds, which used propositions in the head to represent facts in the world and to deduce knowledge. In psychology, behaviorism limited science to empirical study of a subject's externally observable behavior. That was challenged by cognitivism, which argued that learning and knowledge required mediation by the mind, for instance using language and logical reasoning (Chomsky, 1959). Cognitive science's computational theory of mind assumed encapsulated mind with internal representations, memory storage and information processing analogous with those of early computers (Gardner, 1985).

Constructivism and social constructivism followed (Packer & Goicoechea, 2000). They accepted Kant's (1787) philosophical insight that the human mind structures all knowledge of the world. Educationally, this implies that students should be guided to make sense of new information in terms of their own understandings (past knowledge, personal perspective, existing conceptualizations, motivations). While this had radical consequences for educational theory, it still focused on the individual as learner. The resulting "constructivist" theories tended to be uninformative (everything is in some vague sense constructed).

Alternative socio-historically motivated theories then developed based on the dynamic philosophy of Hegel (1807) and Marx (1867), which shaped Vygotsky's, Bakhtin's and other investigators' theories of the social mind and mediated cognition. From the perspective of the emerging socio-cultural framework, cognitive development and learning were results of dialectics between personal tool-mediated activities, group interactions, social practices and "cognitive-cultural macro-structures" (Donald, 1991). This can be viewed as a watershed transformation from individualism to recognition of the group and social community as pivotal to learning, opening the way for CSCL as an educational approach.

"Mediation" is a concept developed in Hegel's dialectical philosophy and central for CSCL. Notice that the word has connotations of media and middle. It can refer to a variety of processes that take place in the middle of two related phenomena. For cognitivism, the human mind plays a mediating role in transforming perceptions of the world into mental knowledge. In CSCL, technologies provide the tools and media through which interactions between people, groups and artifacts take place; they mediate both interaction and materially embodied activity. In CSCL contexts, interaction is not directly between minds, but is mediated by language, gesture, symbol, technology and context (including school practices, background knowledge, previous interactions).

Vygotsky's theory of "mediated cognition" provides an historical cornerstone of CSCL theory.

Development and Learning in Vygotsky

Vygotsky (1930) developed an approach to educational psychology appropriate to the philosophical methods of Hegel and Marx. His writings point beyond individual psychology to a recognition of mediated, group, social cognition. Thereby, they offer an important starting point for CSCL theory.

Collaborative learning, as the source of cognitive development, may be considered a basis of all human learning, not just an optional and rare mode of instruction. That is, group cognition is a foundation of human cognition (planning, problem solving, deduction, storytelling, etc.) at all levels. Vygotsky's experiments illustrate ways in which group cognition forms a base for individual cognition. By incorporating language, external symbols and other cultural artifacts, this process connects the cultural and community level to the small-group and individual levels.

The gap between cultural development and individual learning is what Vygotsky calls the "zone of proximal development" (ZpD). This includes what a child will next be able to learn. It is a prime arena for CSCL intervention because students in this zone can learn collaboratively what they cannot yet learn by themselves. In Vygotsky's (1930, pp. 86f) well known discussion of the ZpD, he cites a study in which children "could do only under guidance, in collaboration and in groups at the age of three-to-five years what they could do independently when they reached the age of five-to-seven years." CSCL can be seen precisely as such an effort to stimulate students within their ZpD—on tasks they cannot yet master individually but are close to being ready to learn—under guidance, in collaboration and in groups.

In his "Problems of Method," Vygotsky (1930, pp. 58-75) called for a new paradigm of educational research almost a century ago. Arguing that one cannot simply look at post-test results of an experiment, he proposed a method of "double stimulation" where a child is confronted by a learning challenge and a potential artifact to mediate that work. Instead of proposing an experimental study for comparing learning outcomes with and without some furnished artifact, Vygotsky suggests that "the experimenter waits until they spontaneously apply some new auxiliary method or symbol that they then incorporate into their operations." Taking this inter-objective research approach on collaboration requires attention to the children's interaction, the object-related activity and the sense-making that is involved in creative, unanticipated collaborative accomplishments.

The essence of Vygotsky's method of double stimulation is the CSCL practice of engaging learners themselves in extended processes of co-creating artifacts for transforming problem situations and re-mediating their learning processes (Ritella & Hakkarainen, 2012); see also (Paavola & Hakkarainen, this volume). Such investigation involves tracing the unique trajectories of distinct groups' *object-related activities*, which could not be understood if sorted into statistically aggregated or standardized categories.

Furthermore, the key role of mediation of group cognition by artifacts—as stimulants to working on a primary learning object—points to the importance of computer support in CSCL. CSCL environments can be designed with a wide variety of artifacts (scripts, models, manipulatives, graphics, prompts, etc.) to stimulate collaborative learning. Vygotsky's brief career began in the context of stimulus/response behaviorism. Through critiquing with a dynamic lens, the theories of learning that were popular in his time, Vygotsky sketched a vision of the ties between individual, group and community (social, cultural) cognition that CSCL researchers can now elaborate.

State of the Art

Recent Theories Influential in CSCL

CSCL is distinguished by its pedagogic, analytic and technological focus on collaboration. Popular *socio-cultural* theories in CSCL build on Vygotsky's initiative. Most traditional and *socio-cognitive* theories of learning, by contrast, focus on the individual mind as the learner and the repository of learned knowledge. The theories presented in this section consider how learning (cognition) and knowledge (epistemology) can be considered at larger units of analysis than the individual human, such as the small group and various social or cultural levels, including artifacts and other contextual referents.

Socio-cognitive Research on CSCL

Socio-cognitive theories of CSCL, which build on conceptions of individual learning, cognition and motivation, typically aim at examining (a) how collaborative group learning affects advancement of individual learning and (b) how manipulations of controlled independent variables affect the success of students' collaborative learning. Investigators may focus on cognitive and motivational gains of personal and collaborative learning or measure the impact of various scripting strategies on collaborative-learning processes and individual-learning outcomes (e.g., Weinberger et al., 2005). Studies of regulation in CSCL have expanded from self-regulation to peer assisted co-regulation and group regulation (e.g., Panadero & Järvelä, 2015). Although socio-cognitive studies often rely on laboratory experiments and quasi-experimental designs, many use mixed methods and collect data from field studies. Each approach has appropriate rigorous standards of evidence that it can follow (Methods section, this volume).

Ethnomethodology

Ethnomethodology contrasts with socio-cognitive approaches in that it does not seek to analyze psychological processes in the minds of individuals, but studies social, interactional and linguistic practices that can be observed directly, for instance in detailed transcripts of conversation. Garfinkel (1967) argued that human behavior is based on the adoption of social practices or "member methods" shared through participation in a given culture. It is because everyone is familiar with these practices that people can make sense of each other's behavior. Furthermore, people display in their embodied activity how their actions should be understood. Sacks studied this in transcripts of ordinary conversation, founding Conversation Analysis (Garfinkel & Sacks, 1970; Sacks, 1965). Investigations showed how people design their speech to open and close new topics, to respond to each other and to repair misunderstandings (Schegloff, 2007). As a sociological approach, ethnomethodology shifts the view of learning to the community, social or cultural level.

Dialogism

Bakhtin's (1981) theory has affected CSCL research by guiding investigators in analyzing dialogic interaction processes. The dialogic approach guides students in sustained interaction that enables them to explore and build on their own and peers' ideas (Wegerif, 2007). From the dialogic nature of thinking and meaning, it follows that a person's utterance in conversation, writing or thinking should not necessarily be interpreted as an expression of private mental representations or beliefs, but as an interactive response to on-going communication, designed to evoke future responses. Furthermore, speech incorporates countless standard elocutions that are part of shared literary genres and language. Often, specific words that someone else used are repeated and taken up in subsequent utterances. Accordingly, utterances should be analyzed and understood as dialogical moves within a social setting, not just as personal expressions.

Knowledge Building

Pioneering CSCL work of Scardamalia and Bereiter (1996) created a knowledge-building framework that engages young students in the collaborative pursuit of knowledge advancement. Their groupware system for mediating knowledge-building processes evolved into Knowledge Forum (see Scardamalia, this volume). They consider knowledge building to be a collaborative effort of advancing communal knowledge, as distinguished from individual learning. They propose that schools can be developed into "knowledge-building" communities that engage students in expert-like creative work with knowledge, appropriating disciplinary methods of advancing knowledge. Toward that end, students are engaged in "design mode" activities of creating, improving, sharing and advancing ideas, understood as improvable conceptual artifacts (i.e., results of knowledge building, such as texts, reports, designs, theories, symbols, tools, usable objects). Knowledge building is an emergent, nonlinear process that cannot be rigidly scripted or pre-determined. The knowledge-building framework has been developed in close collaboration with teachers committed to implementing Scardamalia's (2002) knowledge-building principles in practice (e.g., anchoring learning on real issues and authentic problems, promoting idea diversity and engaging in efforts of reflecting upon earlier investigations or proposals).

Knowledge-Creating Learning

Paavola and Hakkarainen (2014) expanded the conceptually oriented knowledge-building theory by also taking into consideration materially embodied aspects of artifacts (see Paavola & Hakkarainen, this volume). Their knowledge-creating learning approach is distinguished both from the knowledge-acquisition metaphor and the participation metaphor (Sfard, 1998). While the acquisition view represents a "mono-logical" (subjective, mental) view on human learning and the participation view represents a "dia-logical" (intersubjective) view, the knowledge-creation perspective may be understood as "tri-logical" in nature because of its foregrounding interaction between individuals, communities *and shared epistemic objects being developed.* Knowledge creation is anchored by deliberately cultivated knowledge practices, i.e., social practices of working with knowledge artifacts and media (Hakkarainen, 2009).

Cultural-Historical Activity Theory

Relying on Cultural Historical Activity Theory (CHAT) developed by Vygotsky's colleagues, Engeström (1987) investigated CSCL from the perspective of expansive learning. CHAT guides researchers to examine CSCL as an integral part of the contradiction-laden historical development of educational activity, calling for profound transformation of social practices prevailing at schools. Social practices are anchored in dynamic activity systems, which must be transformed to allow significant changes to happen. Expansive learning starts by criticizing, questioning and analyzing contradictions arising within the system or in its external relations. CHAT studies often promote community development by engaging students and teachers in solving vital real-world problems in collaboration with networks of local stakeholders, such as community organizations and workplaces (Engeström, Engeström & Suntio, 2002; Roth & Lee, 2007).

Actor-Network Theory

Actor-Network Theory (ANT) (Latour, 2007) builds on science-and-technology studies showing how complex human activity relies on networks of people, artifacts and practices. Such networks diverge from CHAT activity systems in terms of having diverse kinds of actors exerting causal influences: including non-human agents such as tools, technology-rich environments or knowledge objects. This framework is characterized by "inter-objectivity" (Latour, 1996) in terms of treating humans and artifacts symmetrically and highlighting the active roles of the various actors. ANT has been applied more often in CSCW and workplace situations than in educational or CSCL contexts but appears to have potential here as well (Fenwick & Edwards, 2011). Learning takes place in increasingly complex socio-material environments, which intertwine enacted local practices with virtual and distributed activities. Technological artifacts have a dynamic dual role as agents that oscillate between structuring and constraining as well as directing and expanding activity. ANT examines social engineering involved in negotiating conflicting interests of stakeholders—such as researchers, technology developers, educational administrators, teachers and students—that successful CSCL projects must align.

Group Cognition and Adopting Group Practices

The theory of group cognition (Stahl, 2006; 2020, Investigation 16) is primarily concerned with building knowledge and epistemic artifacts through artifact-mediated processes of group interaction. It focuses on the small-group unit of analysis, as the level at which social and cultural phenomena and artifacts influence the interaction, which, in turn, may produce group, individual and community learning. The theory elaborates concepts of cognition, knowledge, interaction, sequentiality, intersubjectivity, shared understanding, artifact mediation, practice, agency and joint attention appropriate to the small-group level of description. The interpenetration of the social, group and individual cognitive levels can be observed, analyzed and studied in processes involving the adoption of group practices, for instance, in the context of learning geometry (Stahl, 2013; 2016); see (Medina & Stahl, this volume). One can refine CSCL curriculum and *pedagogy* to promote the adoption of key group practices. CSCL *technology* can support the presentation, exploration and adoption of identified group practices. *Analysis* of group interaction in CSCL settings can reveal successes and barriers to adoption of such practices and point to needed improvements as well as documenting successful learning at group and individual levels.

Dealing with Diversity

It is appropriate that a field like CSCL, which is still an exploratory vision, allows a diversity of theories, from subjective to intersubjective and inter-objective. This inspires innovative research agendas. However, because theory has consequences for methodology, a researcher should be explicit about what theoretical framework guides a specific research project or analysis. One's research question should determine the unit of analysis and associated methods. While all established theories capture some truth, when combining approaches, their corresponding methodologies may be both limiting and mutually incompatible. For instance, validated self-report questionnaires are useful tools, but participants' individual responses are not likely to adequately reveal contextual factors and intersubjective learning processes. The current situation of the theory of CSCL affords flexibility to the researcher but requires careful respect for the diverse approaches.

The Future

Toward an Integrated Theory of CSCL

CSCL theory during recent decades has increasingly broadened the phenomena of interest—from learning impacts on individual students to forms of interaction within small groups and communities, involving various forms of artifacts and interactions among levels. Central theoretical concepts have been reconceptualized. Investigation of the phenomena related to these concepts will continue to stimulate theory building and may allow a more integrated framework to emerge for understanding collaborative learning and for guiding technological and pedagogical support.

In this section, we review themes and concepts that seem central to continuing to develop CSCL theory—from a collection of concerns from related fields to a framework specific to what is unique to CSCL (see Figure 2). Finally, we turn from theory to practice and consider the implications of this chapter's discussion for pursuing CSCL in the classroom.

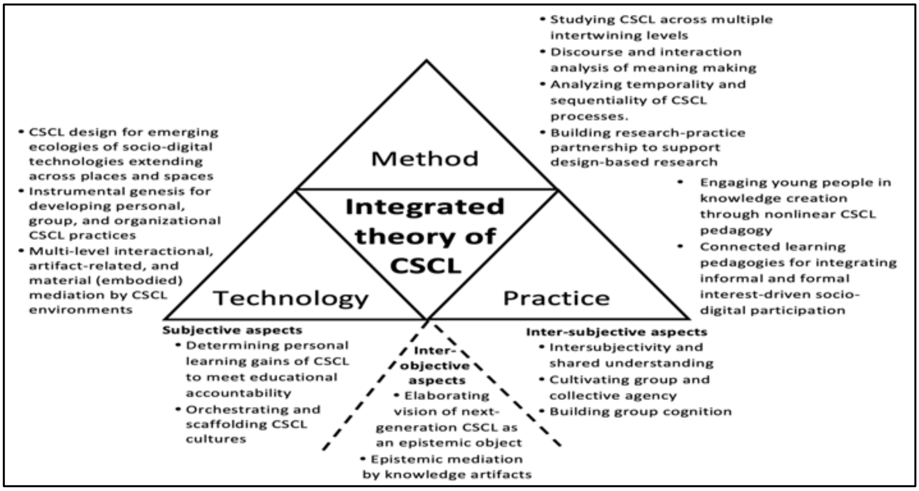

Figure 2. Framework for integrated CSCL theory.

Elements of an Integrated Theory of CSCL

Discourse and Interaction

Collaborative learning proceeds through knowledge-creating discussion within a group of learners. The group learns by building and sharing knowledge and by interacting in non-verbal ways within the CSCL environment (e.g., highlighting, sketching, modeling, prototyping, gesturing, producing knowledge artifacts). Analysis of collaborative interaction usually involves investigating transcripts of the discourse and multimodal interaction. It may consist of understanding the flow of conversational moves and embodied actions and the meaning making that took place by the group, perhaps adapting Conversation Analysis (Schegloff, 2007) or Interaction Analysis (Jordan & Henderson, 1995).

Interactional Mediation by CSCL Environments

CSCL provides multi-faceted socio-technical environments that mediate collaborative interaction and learning in diverse ways. The rapidly evolving ecology of socio-digital technologies is distributed across formal and informal spaces of learning, so that technology mediation is increasingly mashed up to take place through and "around" socio-digital tools. Theory should account for such mediation and inform the design of media to support specific, identified aspects of collaborative learning, as well as interconnecting informal and formal technology-mediated learning.

Epistemic Mediation by Knowledge Artifacts

CSCL environments offer learning communities shared spaces and scaffolding for creating, building, visualizing, sharing, organizing and advancing knowledge artifacts. Socio-digital technologies enable cognitive augmentation that CSCL builds on: By technologically extending the mind, digital devices foster new forms of collaborative working and engagement in successive refinement of complex ideas (Donald, 1991). The "epistemic mediation" involved in such extended thinking processes refers to a deliberate process of deepening inquiry by creating external epistemic artifacts (e.g., shared written notes, visual representations, material artifacts, simulations and discourse media) that crystallize and promote evolving understanding and collective inquiry. Problems and solutions in CSCL processes can be understood as epistemic objects; such objects represent what the participants are seeking to understand and create but do not yet know or understand. These objects are defined by their openness, incompleteness and capacity to unfold indefinitely through successive thought- and affect-laden instantiations as textual or other artifacts (Knorr-Cetina, 2001).

Temporality and Sequentiality

CSCL takes place over time and through language use embedded in technology-mediated activity. Interaction takes place through the sequential ordering of actions, utterances and gestures. A given oral or written utterance typically responds to previous activity and discourse, generally designed to provoke a response and to propel the discourse and inquiry forward. The analysis of collaborative learning as a group meaning-making process may need to interpret the temporality and sequentiality of captured discourse and related activity (Medina & Stahl, this volume).

Although utterances may be analyzed statistically to answer specific research questions, the enacted collaboration itself is an inherently sequential process, which cannot be fragmented without losing its meaning. Further, temporality and sequentiality also structure the non-linguistic activity. CSCL activity is embedded in unfolding social (group work) and material (technological) processes, which are entangled in temporal emergent assemblages, analysis of which may reveal development of key epistemic, group and social practices. For instance, analysis at multiple time scales can reveal processes at the micro level (e.g., utterances), meso level (establishment of group practices) and macro level (evolution of community cultural norms).

Intersubjectivity and Shared Understanding

A fundamental theoretical question for CSCL is that of intersubjectivity (Stahl, 2020, Investigation 18): How is it possible (both in the abstract and in practical terms) for participants in a group to understand each other? This is a problem for cognitivism: If one person's mind expresses a thought in a spoken utterance, how can another person's mind know what that utterance meant to the speaker? Socio-cultural theory answers this by noting that people share language, activity context and cultures laden with mutually understood meanings. Of course, in a situation of collaborative learning there are ample opportunities for misunderstanding each other. Fortunately, our languages and embodied activity include shared practices for repairing misunderstandings. Intersubjectivity is the result of specific aspects of human interaction, beginning in prehistory (Tomasello, 2014) and continuing in successful CSCL sessions today (Schneider & Pea, 2013). The need to constantly maintain intersubjective shared understanding is a major reason that CSCL requires special supports, training and effort in order to be successful.

Personal, Distributed and Group Agency and Units of Analysis

Theories based on individual minds locate the agency that causes events like expressing opinions or learning at the individual unit of analysis, looking to personal motivations and beliefs. Theories of distributed cognition (Hutchins, 1996) or group cognition locate collaborative agency at the group unit. Activity Theory (Engeström, 1987) looks as well at tensions or contradictions among social factors in the setting and Actor Network Theory (Latour, 2007) goes even further to bestow agency on an open-ended universe of (past and present) human and artifact actors, bringing in a cultural-historical unit of analysis. CSCL theory should account for agency and other phenomena at multiple units of analysis.

Orchestrating and Scaffolding the CSCL Culture

An early finding of CSCL research was that collaborative learning cannot succeed in classrooms without preparing teachers and students with an understanding of the theory and pedagogy of CSCL. A classroom culture of collaboration must replace the culture of individual rote learning and competition. CSCL aims at cultivating "nonlinear" pedagogy, characterized by open-ended, emergent and inventive educational practices (Ng, 1995). Although nonlinear knowledge-creation processes cannot be rigidly scripted (Scardamalia & Bereiter, 2014), it is necessary to guide and scaffold student learning for productive collaborative learning, interaction and knowledge creation. Flexible teacher orchestration and CSCL structuring is required to cultivate local practices of working with knowledge and media (Zhang, et al., 2018). A delicate balance is needed for guiding, scaffolding, orchestrating, structuring and facilitating collaborative knowledge creation.

CSCL theory must recognize these implementational requirements and point the way to the desired vision. The theories just enumerated offer insights into what learning and knowledge building might be like in effective CSCL contexts. They supply concepts and frameworks for thinking about such collaborative processes. They also provide guidance for CSCL research into the design and trial of technology and pedagogy for supporting CSCL.

Theoretical Perspectives on Implementing CSCL

Implementing the Vision of CSCL in Classrooms

CSCL has been criticized for having failed to transform education (e.g., Wise & Schwarz, 2017). Critics assume that once students had computers and became accustomed to networking with other students, the incorporation of collaborative learning and CSCL in classrooms should have spread rapidly. We all seriously underestimated the challenges of transforming technological infrastructure, cultivating CSCL practices and changing associated educational accountability regimes. The preceding theoretical perspectives indicate why implementation of CSCL will take longer:

- CSCL is a *vision* of a future involving technologies, practices and research methods that guide investigators' theory-building and intervention efforts. CSCL is an incomplete epistemic object (Knorr-Cetina, 2001), which constantly raises new questions and becomes more complex as technologies, practices and methods develop unpredictably.

- CSCL is embedded in rapidly expanded *ecologies of socio-digital participation* that involve young people using technology intensively. Many young people use digital technologies for pursuing their interests together with their peers, experimenting with digital tools and making personal media productions. The challenge of CSCL is to promote connected learning in terms of also engaging students at school in creative and academic collaborative use of technology for knowledge building (Ito et al., 2013).

A theoretical and practical challenge is to determine what processes, methods and practices are needed for CSCL to penetrate deeply into educational systems. A handful of systematic efforts have produced promising results (e.g., Chan, 2011; Looi et al., 2011), but they have been rare. Although there have been isolated CSCL classrooms sustained by committed teachers, the establishment and dissemination of rich collaboration cultures in schools remain elusive and prone to failure (Hakkarainen, 2009; Ritella & Hakkarainen, 2012). Advancement of the CSCL field requires a more comprehensive theoretical and practical understanding of the complex and dynamic relations between digital technologies, social practices and educational-transformation processes.

Despite transformative CSCL visions, new digital tools tend to be initially used to promote traditional practices of teaching or learning; radical innovative possibilities emerge only through sustained transformation of social practices (Hakkarainen, 2009). Successful implementations of CSCL practices rely on systematic participatory transformations taking place through intensive research-practice partnerships. To effectively utilize CSCL practices, teachers and students must undergo "instrumental genesis" (Rabardel & Bourmaud, 2003), integrating the CSCL tools into learning/teaching activities. This involves shaping, adapting and tailoring the CSCL tools and practices according to local needs and requirements by participants, as well as cultivating novel personal and group practices. The process iteratively evolves the design of the tools to better facilitate intended practices and the creation of novel practices, tool usages and understandings by the participants.

As students increasingly rely on technology in their everyday interaction, cognition and learning practices, approaches explored in CSCL research and theory may promote connected learning practices and, thereby, overcome the limitations of simplistic social-media apps. The result may be quite different from the experimental prototypes of classic CSCL research projects. Despite the complexity of the challenges, that is what it means to understand the CSCL vision as an epistemic object of global inquiry, rather than as a summative evaluation of a well-defined object of study. Theories of CSCL should comprehend, envision and guide the targeted transformations and emergent technologies, practices and methods for achieving the CSCL vision.

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Scardamalia & Bereiter's argument for supporting collaborative learning, among other seminal papers.

- Vygotsky, L. (1930). ***Mind in society***. Cambridge, MA: Harvard University Press. – Vygotsky's most important writings and notes collected here present a vision of the theory of learning most influential in CSCL.
- Donald, M. (1991). ***Origins of the modern mind: Three stages in the evolution of culture and cognition***. Cambridge, MA: Harvard University Press; Donald, M. (2001). ***A mind so rare: The evolution of human consciousness***. New York, NY: W. W. Norton. – In these books, Donald presents culture as a rapid form of human evolution and extends the theory of learning to include external memories provided by digital technology.
- Stahl, G. (2020). ***Theoretical investigations: Philosophical foundations of group cognition***. New York, NY: Springer. –This edited volume brings together many of the past articles in the *International Journal of CSCL* and recent essays by the journal's editor that are most relevant to this chapter. Together, they point in the direction of CSCL theory indicated here for the future. See also (Medina & Stahl, this volume) and essays available at: http://gerrystahl.net/elibrary.
- Hakkarainen, K. (2009). **A knowledge-practice perspective on technology-mediated learning**. *International Journal of Computer-Supported Collaborative Learning. 4*(2), 213-231. – This article generalizes research experiences implementing CSCL in educational practices, expands knowledge building toward the trialogic approach to knowledge-creating learning and works out the notion of knowledge practices. See also (Paavola & Hakkarainen, this volume).

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3. Analysis of CSCL

Richard Medina and Gerry Stahl

Abstract. This chapter introduces an approach to CSCL research driven by the analysis of data displaying how groups adopt, adapt and master new collaborative knowledge-building practices. The analysis of group practices can provide unique insight into the accomplishments of teams of students in CSCL settings. It conceptualizes a theory of learning with the group as the unit of analysis in terms of the acquisition of group practices. CSCL pedagogy can then be oriented toward orchestrating the adoption of targeted group practices, supported by CSCL technology.

Keywords. Ethnomethodology, group practice, group cognition, interaction, orchestration, representational practice, segmentation, sequential analysis, social practice, unit of analysis, uptake.

Definitions & Scope: Learning as Acquisition of Group Practices

Theory: Group Practices as Group-level Constructs

This chapter provides a view of small-group practices as central to computer-supported collaborative learning and, indeed, foundational for all human learning. Rather than conceptualizing learning as the accumulation of explicit knowledge, such as the memorization and storage of facts stated in explicit propositions, one can view cognitive development in terms of tacit practices: knowing how to do things, to behave, to respond, to contribute, to solve specific kinds of problems, to formulate explanations. In CSCL, this involves focusing on group practices as the constituents of collaborative learning, which can be acquired by groups of learners.

A "group practice" as conceived here is a group-level construct. That is, it is to be distinguished from, for instance, psychological constructs on the level of the *individual* mind, such as mental representations or thoughts. On the other side, it is distinct from *social* practices as studied by social sciences oriented to institutions, communities, cultures or societies. A theory of CSCL oriented to group practices needs to re-conceptualize all the categories of thinking, knowing and learning at the *group* level.

A focus on group practice in no way denies the existence and importance of individual thinking, knowledge, skills, habits, inclinations, emotions, etc. Nor does it dispute the power of social practices and cultural resources. Rather, practices and other cognitive or epistemological constructs at the individual, small-group and community levels are seen as interacting with each other intimately.

Although it is particularly difficult to find adequate detailed interaction data to analyze the mechanisms of inter-level influences, it is clear that individuals acquire their major cognitive tools like language, narration or argumentation from their larger cultural context, and that such acquisition takes place through small groups such as their immediate family, close friends, gangs, tribes or teams. The following slogans are suggestive of this: "It takes a village to raise a child" and "All I know I learned in kindergarten." These are settings in which young children acquire language, social behavior and norms of interaction. If you look closely, you see that this happens overwhelmingly in games, disputes and modeling within dyads, triads and other small groups within the extended family, village or kindergarten, including between adults and children as well as among peers—largely through imitation and repetition.

Empirical analysis of group practices (see Additional Readings below) shows that a typical learning process happens as follows, with interactions among different levels of description:

- A small group adopts a practice that may have been introduced into the group by one of its members or been drawn from the larger culture.
- The small group may try out the practice and even discuss it explicitly to some extent.
- If the group adopts the practice, it becomes a resource for future behavior of that group and may then be used tacitly, without further discussion.
- Subsequently, members of the group may adopt the group practice as their own individual skill, having learned it collaboratively.

Small-group practices can also have effects in the opposite direction, influencing their communities. Over historical timespans, cultures have evolved new practices for constructing knowledge by adopting practices of small groups. These can then be spread to their citizens through acquisition by small groups and subsequent adoption by individuals. For instance, small groups of ancient Greeks developed the practices of geometry, which included formulating deductive proofs (Netz, 1999). The practices of proving were then acquired by groups of Greek philosophers and eventually adopted throughout Western culture as practices of argumentation (Latour, 2008). In each generation, these practices were introduced to groups of students and ultimately adopted by individuals as rational thinking.

Pedagogy: Curriculum for Acquiring Group Practices

The recognition of the centrality of group practices to human learning can motivate an approach to pedagogy. Teaching can be driven by the goal of encouraging small groups of students to acquire group practices that are considered foundational to a given academic domain. For instance, school geometry involves practices of constructing and labeling figures, proving theorems and identifying dependencies of geometric elements upon each other.

Analysis of interaction among small groups working on geometry problems in a CSCL environment has identified the adoption of numerous relevant group practices (Çakir, Zemel & Stahl, 2009; Medina, Suthers & Vatrapu, 2009; Öner & Stahl, 2015; Stahl, 2016). The accumulation of these practices by the groups constituted their collaborative learning of the subject. Further analysis at other levels could reveal consequent changes in individual knowledge and in classroom instructional practices.

Design: Planning to Sequence Group Practices

Pedagogy associated with CSCL approaches to teaching a given subject can be designed to promote specific identified practices. It is always important to ensure that groups have acquired basic *collaboration practices*, such as taking turns, involving all group members, directing joint attention and maintaining common ground. There are also practices involving using the available *technological* affordances. In addition, groups must acquire the important practices of the *subject matter*. Then, they need to employ *discourse practices* to maintain group agency and to reflect upon their collaborative learning.

Because learning takes place through intertwined levels of individual, small-group and community processes, it is important to design mutually supportive mechanisms for different levels and to orchestrate their application. For instance, teacher-centered presentations and individual reading of background information can motivate and orient small-group CSCL activities that follow. The group activities in turn can be reinforced through whole-class discussion that presents, compares and reflects upon the groups' knowledge artifacts. Effective orchestration of activities can coordinate and mutually reinforce related individual, group and social practices.

Technology: CSCL Supports for New Group Practices

All these practices can be designed into a CSCL environment through sequencing tasks, providing resources and carefully wording instructions, as well as design of domain-specific technology for construction and modeling. For instance, mechanisms that provide relevant textual information can introduce practices that are established in the broader culture, such as standard procedures.

Shared spaces in a collaborative online environment can support joint attention and stimulate shared exploration leading to group practices. Persistent summaries of collaborative learning can enable the establishment of individual knowledge. Affordances like text highlighting, eye-tracking display, line-coloring options and pointing tools can support joint attention and shared focus within digital group workspaces (Çakir et al., 2009; Schneider & Pea, 2013).

Methodology: Analysis of Adopted Group Practices

For educational researchers, an important question is how an observer can know what practices groups have acquired. If all the group interaction has taken place within a well-instrumented CSCL environment, then the necessary data may be readily available for analysis. This assumes that all interaction, including both discourse and visual presentation (drawing, pointing, construction sequence, highlighting, etc.) has been captured and preserved in the data corpus.

Whereas mechanisms of individual and community learning may involve unobservable processes like mental modeling, individual motivation or social dispersion, the acquisition and performance of *group* practices are necessarily public processes. The discourse moves that make up the acquiring of new group practices must be available to the members of the group to allow them to work together. Consequently, researchers may be able to see the same things as the group members display to each other.

Of course, the researchers observe their captured data from a distanced analytic perspective, whereas the members interact to the fleeting original displays from within their active engaged perspectives. The students may not be aware of their involvement in the adoption of group practices; this is usually a tacit process, which is not articulated in the minds or speech of the participants. However, researchers can analyze and document the process. This chapter will suggest procedures for doing this kind of analysis of the adoption of group practices— particularly through methods of interaction analysis.

History & Development: From Individual to Group-Level Constructs

Prehistoric Spirits as Explanations of Expertise

How learning takes place, how knowledge is developed, and how some individuals gain above-average expertise are questions that have always been raised. In olden times and ancient cultures, the answers often involved external, non-human sources such as spirits, ephemeral voices or special gods. For instance, artists were inspired—that is, filled from outside with spiritual substances—perhaps by their muse or by divine guidance.

Later, expertise was attributed to a mysterious quality of genius. In this view, it was considered an attribute of an individual person. However, the source of this attribute was not subject to explanation or investigation.

Alternatively, knowledge was taken as a mythic attribute of a culture. The intelligence or sophistication of members of one culture was considered more advanced than that of members of other cultures, who were branded as barbaric or primitive.

Rational Minds as Thinkers

Modern views treat an individual's behavior and knowledge as rooted in a rational mind. This approach parallels the development of science and is mirrored in the history of Western philosophy. Science dispensed with the world of spirits, eventually substituting hypotheses about mental representations, neural networks and social institutions.

Plato (340 BCE) argued against explanations involving Greek gods and situated truth in the efforts of the self-reflective individual. Aristotle (330 BCE) developed the first system of logical inference and pursued empirical investigation to discover knowledge. The conception of man as a rational mind reached its extreme expression in Descartes' (1633) philosophy, which was expanded in Kant's (1787) analysis of pure reason as the product of each individual human mind.

Rationalist theories still dominate much of science and popular thought. Economics and psychology, for instance, often model people as rational decision makers or as deductive reasoners. However, philosophy since Hegel (1807) paints a more dynamic picture in which human knowledge and reasoning develop over time through interaction with others in groups and cultures. Scientific theories relevant to CSCL have followed various philosophic trends of the past two centuries.

Individuals Constructing Understanding

Constructivist theories (e.g., Cobb, 1994; Packer & Goicoechea, 2000) argue that students necessarily construct new knowledge for themselves, using their existing conceptualizations and past knowledge. This is a Kantian view of explicit individual knowledge. Polanyi (1966) proposed an alternative view of knowledge as being primarily tacit. For instance, children learn to ride a bike through bodily feelings that are not spoken in words.

The perspective of tacit knowledge can be generalized to apply to most learning. We learn without being explicitly aware of the processes of learning or articulating them in speech or thought (silent self-talk). Rather, we learn through mimesis (imitation) and routine (repetition). Tacit learning typically takes place in interaction with others in dyads, family units or small groups. It is largely preserved in habitual behavior.

Social Practice

Theories of social practice (Bourdieu, 1972/1995; Giddens, 1984; Goodwin, 2013; Lave, 1988; 1991; 1996; Lave & Wenger, 1991; Reckwitz, 2002) can be considered a natural consequence of this move away from rationalist theories to tacit conceptualizations. Social practices are not the result of explicit negotiation, agreement or social contract. They arise tacitly through interaction and habituation. Theories of social interaction have been developed by social scientists (anthropologists, sociologists, linguists), so they generally locate the practices at the level of society, culture or community. However, most of their empirical examples of social practices take place situated in the interaction of small groups, such as apprentices with their master (Lave & Wenger, 1991). For CSCL, the theory can be re-conceptualized and studied at the small-group unit of analysis.

Perhaps the most detailed analyses of social practices have been carried out in the field of ethnomethodology and conversation analysis. The following sections review major findings of this research. For additional rendering of qualitative analysis, including conversation analysis, see Uttamchandani & Lester (this *Handbook*).

Ethnomethodology and Sequential Organization

The sequential ordering of situated interaction is a central characteristic of joint human activity. An instance of human communication can be seen as a temporally unfolding series of communicative actions. How these actions relate from one moment to the next and from one participant to another within a setting has been the empirical focus of ethnomethodology (EM) and its applied field, conversation analysis (CA) (Garfinkel, 1967; Goodwin & Heritage, 1990).

One of the systemic aspects of sequential organization of interaction explored in CA is the notion of *turn taking* (Sacks, Schegloff & Jefferson, 1974). A turn is defined by an adjacency pair where one utterance by one participant is followed by a second utterance by another participant. For example, a greeting, such as "How are you?" invites a response, such as "Fine!" at the appropriate next speaking opportunity. This is an oversimplification, as offering no response may be taken as a (non)-response, thus opening up a range of relevant subsequent sequential mechanisms, or turns, to be worked.

This greeting example illustrates an important consideration for our analysis of small-group practices: The sequential structure of joint human activity is fundamentally negotiated. Issues emerge in our joint activity (e.g., the relevance or irrelevance of the non-response) that shape other courses of action and their sequential structures. Studies in CA have identified and described these kinds of sequentially organized structures in a multitude of different settings. The notion of a turn-taking system offers an analytic framework for investigating how interactions might vary structurally within and across specific settings (e.g., casual telephone conversations versus doctor-patient consultations). Turn-taking in a variety of different discursive settings reveal a number of different contingencies, such as the number of parties involved in the interaction, the organization of topic openings and closings, and the allocation of turns (Schegloff & Sacks, 1973; Schegloff, 1990). Thus, the analysis of turn taking forms an empirical foundation for tracing discernable practices within small-group interaction.

Interaction in the Setting

The turn-taking apparatus advanced by CA practitioners has served as a productive analytic tool for clarifying the relationship between setting and interaction. Schegloff (1991) refers to how the external elements (anterior to language) of the situation are made *relevant* and *consequential* for the interaction, i.e., how participants' immediate actions are contingent on resources in the setting for coordinating and ordering their interaction. These resources include the stream of talk preceding the next utterance as well as the semiotic and material elements that make up the setting and are referenced in the interaction.

This notion of relevance requires that analyses seek the points in interaction in which participants organize and account for referents in the conduct of sequential action (turn-taking structure). Procedural consequentiality highlights those instances in which the setting itself (e.g., courtroom vs. living room) informs and shapes sequential structures. This view is particularly noteworthy for CSCL, as our concern is the impact that rich semiotic settings and technologies have on collaborative-learning processes.

Multimodal Sequential Analysis and Representational Practice

A wide variety of studies have leveraged the analytic insight of EM and CA to draw attention to the configuration of the speaker's body, the semiotic elements of the setting and their coordination in the sequential organization of action (Goodwin, 1994; 2000a; 2018; Streeck, 1996). Goodwin's studies consistently demonstrate how the semiotic, material and embodied elements of the setting are relevant and consequential to the structure of interaction. Action is not limited to utterances but is distributed across a range of multimodal resources available to participants. Discussions of indexicals—how language references elements of the setting—in this regard are often central to explaining and describing the role of media artifacts (Zemel & Koschmann, 2013). Goodwin (2013) convincingly argues, however, that the semiotic environment is not limited to reference, but is itself manipulated in communicative action. One of Goodwin's formidable contributions is how semiotic action is included in structural explanations of human interaction (Goodwin, 2018).

EM and CA traditions specify the focus of inquiry on the sequentiality of interaction. In so doing, they afford a starting point for empirical analysis of technology-mediated interaction that tightly couples user actions with the particulars of the setting. In CA generally, the setting is established through talk. Other similarly motivated lines of work such as that by Goodwin extend analysis by including semiotic, material and embodied elements of the setting. There has also been some analysis of how sequentiality and turn-taking unfold in CSCL settings such as text chat (Zemel & Çakir, 2009).

The following section discusses the concept of *uptake* as a reformulation of sequentiality with particular relevance to CSCL.

Uptake as the Unit of Interaction

Making sense of the sequential structure of interaction and its deployment within CSCL environments presents a degree of complexity for analysis. Interaction settings may be asynchronous or synchronous, and participants may be co-present or geographically distributed. Further, CSCL actions may extend beyond the verbal modality: dragging an object across the screen or posting a graphic. Participants can draw upon semiotic, material and embodied elements of the setting in organizing their interactions. A useful strategy to begin with might be to recognize how participant actions are evidenced to be relevant and consequential for activity. How and where are actions positioned in the sequential unfolding of the larger activity, and how do those actions relate to prior actions? The notion of *uptake* has been proposed as a useful concept for investigating precisely these questions.

Suthers, Dwyer, Medina and Vatrapu (2010) describe uptake as a relational construct that identifies a participant action as appropriating aspects of a prior or ongoing setting as relevant for ongoing interaction. This definition is deliberately abstract, enabling it to be purposed in a wide range of interactional analysis. It is also intended to support a diverse range of theoretic and methodological approaches. Uptake specifies a relation between a user action and some aspect of the environment. A potential gain of interpreting interaction as uptake is that uptake does not privilege one particular communicative modality (e.g., verbal adjacency pairs) or granularity over another. A warranted interpretation of uptake only specifies that one human action is appropriating aspects of a prior or ongoing element of the setting while also transforming that setting. The value of uptake for the analysis of technology-mediated interaction is its provision for a more flexible consideration of sociological and technological contingencies. This value also extends into analytic interpretations and reportable findings, as discussed below.

Group Cognition

Focusing on uptake or the adjacency pair as the unit of interaction locates research at the small-group level of the discourse or shared cognition that takes place between or across individuals. It includes contributions from two or more individuals, but cannot be reduced to a mental achievement of either individual, or even a simple sum of their mental representations. The parts of the uptake or adjacency pair elicit and respond to each other, thus happening outside the heads of any one participant, but constituting a relationship among them. The relationship necessarily takes place in the public arena of the group, where it is shared by and visible to the participants (and potentially to researchers). The cognition that takes place here is an achievement of the group as such; it can be conceptualized as *group cognition* (Stahl, 2006).

The analysis of group cognition in terms of interaction through adjacency pairs or intersubjective meaning making through uptake (Suthers, 2006) provides a methodological basis for studying the adoption of *group practices* as the origin of collaborative learning. It thereby offers a rigorous approach to the study of CSCL, including a method for providing feedback to the iterative design of CSCL interventions. We now consider a procedure to conduct such analysis.

State of the Art: Analysis of Group Practices at Multiple Sequential Orders

This section outlines a methodological approach to analysis of group practices. The approach builds on foundations of ethnomethodological inquiry by maintaining a primary concern with the sequential organization of interaction (Jordan & Henderson, 1995; Schegloff, 2007). The overall strategy of the approach attempts to provide a hierarchically organized account of observed practices by identifying different structures of sequential interaction as data points (or segments). When fully assembled, these structures provide an informative view of the hierarchical and sequential processes of small-group interaction in CSCL settings (Stahl, 2020, Investigations 16, 24, 25). Thus, our goal is to build a structural description of observed interaction that can be used as a resource -- within the larger understanding of small-group interaction sketched above -- for addressing various research questions and contributing to different theoretical and applied research agendas.

The steps of the analysis presented here are extrapolated from the "Eight C's" outlined by Fisher and Sanderson (1996). Their approach to Exploratory Sequential Data Analysis (ESDA) enumerates a succession of analytic activities for handling observational data. The intent behind the set of procedures is to progressively arrive at a structured understanding and representation (referred to as "smoothing") of sequential data records. The smoothing process adapted for this description can be seen as working with multiple, mutually compositional units of analysis: (a) microanalysis (documentation of turn-by-turn relevancies), (b) structure (determination of interactional structure) and (c) macro-structure (formation of interactional structures such as group practices).

Our procedure applies three of the eight ESDA smoothing operations as relevant for analysis of small-group practices. These operations are (1) segmentation into chunks, (2) descriptive comments and (3) relational connections (see Figure 1 and following sections). It is important to note that the procedure is iterative, moving back and forth from one smoothing operation to the other as the analysis unfolds.

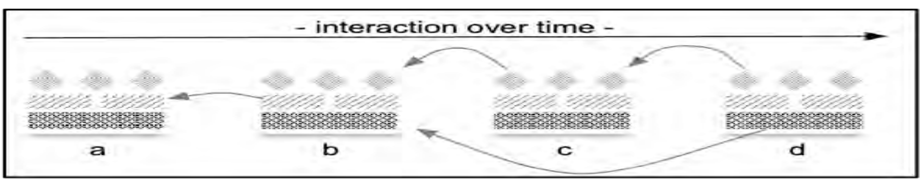

Figure 1. Illustration of four segments each composed of subsequences at different granularities.

0. Content Logging

An initial pass over the data is conducted to establish and mark off major sections of the data stream and possibly to synchronize time indices across multiple data sources (e.g., video and software-generated log files). Content logging is a preparatory step, crucial for gaining a sense of the scope of the activity captured. After the initial logging, analysis cycles through the three relevant ESDA operations.

1. Segmentation

Segmentation is the identification of boundaries between adjacent interaction events that together form a sequential structure. A data element at the lowest granularity is an elementary participant interaction (e.g., a conversational turn). Participant actions are sequentially organized within the interaction, creating boundary points for segmentation. These segments may range from short exchanges such as a reply to a question or may extend into longer structures concerned with, for example, specific topics or problems introduced by the participants. The purpose of this smoothing technique is not to reorder the continuous nature of interaction in its setting, but to identify its elements and structure in a tractable manner. Identified segments, on further analysis, may contain smaller chunks or segments. Figure 1 provides a schematic of this process. Each of the four labeled segments may contain sequential structures within it identifiable at different granularities.

An important analytic feature that emerges as a result of segmentation is the transition between segments. A transition may be acute, such as the boundary between two separate days of interaction. The gaps between a, b, c and d in Figure 1 indicate this kind of boundary. Transitions may occur within particular episodes more subtly, such as a signaled change of topic or focus (e.g., the gaps between the inner shapes in Figure 1). In general, transitions between segments may dramatically expose the organizational and coordinative work involved in interactional practices (Jordan & Henderson, 1995).

In addition to the segmentation of observed interactions in the data set, it is possible to adjust analytic focus on aspects of the data that are of concern for a research study. For example, a segmentation analysis could be conducted on inscriptional activity involving CSCL text or drawing tools. Focused segmentation, in this case, would result in sub-sequences of inscriptional activity occurring within longer segments of interaction.

2. Segment Description

A segment is then analyzed in a turn-by-turn approach strongly influenced by techniques used in CA. A turn unit consists of an utterance or chat contribution, gesture, gaze, drawing or manipulation of the interaction environment. At a fine granularity, we look at the relationship between actions to determine how the prior turn is taken up or handled by the next turn, which it may have elicited. This close inspection typically yields the identification of communicative mechanisms.

Microanalysis of a segment is recorded as annotations that might draw on technical terms commonly utilized in CA studies or, alternatively, as emergent vocabularies for describing the interaction structures observed. The result of this phase is a mixture of common technical terms, labels and terms deemed adequate by the analyst in documenting a segment.

3. Relations Among Segments

The next step in the procedure identifies and describes connections among segments, some of which may extend beyond immediate interaction contexts or may form repeated behavioral patterns, or *group practices*. Figure 1 illustrates how the scheme is utilized to determine connections: arrows between segments indicate relations that emphasize the *contingency* or *relevance* of one segment to another. Evidence for drawing connections between segments is based on the following baseline heuristics:

- Uptake of prior resources.
    - Using references to prior elements ("indexicality").
    - Transporting prior elements into the current context ("temporal bridging").
- Invocation of a prior (established) sequential structure (a conversational "social practice" or a local "group practice").
- Anticipatory projection of a future (desired) element ("group agency").

The microanalysis of segments conducted in steps 1 and 2 above provides an empirical frame in which to observe how the participants orient to and make relevant their talk as well as their action. A critical component for making these observations of sequential structure and its elements is the identification of referents that evidence indexical relations between and within turns. Referents that are under-determined in the immediate interaction but can be located in prior observed situated settings warrant the identification of a connection (e.g., the arrow between d and b in Figure 1). These "missing" referents provide a demonstration of how prior situated activity is made relevant and consequential for immediate turn-taking sequences (Koschmann, LeBaron, Goodwin & Feltovich, 2001; Koschmann, Sigley, Zemel & Maher, 2018; Medina et al., 2009).

Another heuristic that is applied to determine connections between segments is based on the identification of *procedural consequentiality*. Here, we explicitly examine how the contextual setting facilitates, conditions and constrains immediate actions. Technology-mediated settings are participant-enacted spaces configured through use, which support the redeployment of discernable actions (Drew & Heritage, 1992; Robinson, 2013). Identifying these actions and their relationship to the setting enables the analyst to form empirically grounded claims about observed group practices.

4. Identifying Adoption of Group Practices

The methods just reviewed have been applied to the identification of group practices in a number of case studies of mathematics problem solving by groups in CSCL environments (Çakir, 2009; Koschmann, Stahl & Zemel, 2009; Öner, 2016; Stahl, 2009; Zemel & Koschmann, 2013). Some of these studies have applied interaction analysis to "longer sequences" of adjacency pairs, as are required for mathematical problem solving (Stahl, 2020, Investigations 23, 24, 25). The analysis of the group interaction must demonstrate how participants make their references relevant and how they establish the procedural consequentiality of their practice within their shared situation.

A group practice can be identified as a segment of interaction that a group periodically repeats in response to certain conditions. If a group is learning/acquiring a new practice, sequential analysis may be able to capture group interactions exploring and deciding upon the new behavior to adopt. For instance, a group of math students might develop a geometric construction procedure through considerable exploration and debate and then adopt it as a regular technique in similar future problems. In mathematics, when such practices are accepted into the broader culture, they may be called "theorems;" once proven explicitly, they can be applied without discussion (Husserl, 1936/1989). Knowledge grows through the acceptance and application of practices and their associated artifacts—by individuals, small groups and communities.

A longitudinal study of a small group learning online collaborative dynamic geometry identified the adoption of about 60 group practices, including practices of: collaboration, problem solving, geometric construction, technology usage and explanatory discourse (Stahl, 2016). Other case studies have applied this approach to rich data sets containing multiple video and screen recordings of small-group interaction in a science classroom (Medina, 2013). These case studies point the way for a new vision of CSCL, centered on the analysis of group practices.

5. Computer-Supported Analysis of Group Practices

The above approach to analysis and identification of group practices can be supported by data-driven research agendas that require cataloging segments and annotations and involve linking segments to data in video, log files or other primary sources (e.g., Dyke, Lund & Girardot, 2009). For example, if segments are viewed as n-gram data points, opportunities arise for automated pattern detection, feature extraction and other computational methods for processing and investigating sequential structures. To the extent that computer analysis of group practices can be accomplished in real time, it could contribute to learning analytics, potentially informing teachers about which groups adopted certain targeted practices.

The Future: Fostering Group Practices

Theory: Acquiring Group Practices

CSCL can be re-conceptualized as the support of groups of learners to acquire group practices that contribute to their collaborative learning. Collaborative learning itself can be conceived in terms of the adoption of specific group practices, which provide various aspects of the group's cognitive abilities. Since individual students often adopt for themselves practices that they first acquired as part of a group-cognitive experience, and communities often evolve new social practices through the transmission of these group practices, collaborative learning and group practices can be considered to play a potentially central, foundational role in human learning at all levels.

Contemporary theories of practice (such as Bourdieu, 1972/1995; Goodwin, 2000b; Hakkarainen, 2009; Lave & Wenger, 1991; Lipponen, Hakkarainen & Paavola, 2004; Medina et al., 2009; Polanyi, 1966; Reckwitz, 2002; Schatzki, Knorr-Cetina & Savigny, 2001; Suchman & Trigg, 1991) reject the traditional rationalist, cognitivist and individualist views of learning, thinking and knowing. They re-conceptualize the basic processes and products of cognition as largely tacit, habitual practices.

For CSCL, with its focus on collaborative meaning making within small groups in computer-mediated contexts, the practice-oriented conceptualizations of these social theories must be shifted to the group unit of analysis. Underlying effective collaborative learning is the maintenance of *intersubjectivity*, the ability of participants to understand and interact with each other. Intersubjectivity is based on our living in one world as the ultimate context of our understanding (Stahl, 2020, Investigation 18) and is maintained through the establishment of common ground through interactional mechanisms such as repair of misunderstandings (Clark & Brennan, 1991). Mutual understanding is supported by *joint attention* to the object of consideration (Tomasello, 2014). Knowledge that contributes to collaborative learning or that results from it is necessarily *shared knowledge*. Intersubjectivity, joint attention and shared knowledge are some of the many group-level constructs needed for a theory of CSCL oriented to group practice (Stahl, 2020, Investigations 19, 20, 21).

Pedagogy: Sequencing Group Practices

Analysis of group practices has been carried out largely with interaction data on virtual math teams engaged in mathematical problem solving of middle-school combinatorics and dynamic geometry (Stahl, 2009, 2020). This is because interesting usable data was available from these instrumented online sessions. The same approach could be applied to other learning domains if adequate process data is collected. For instance, a number of CSCL researchers have studied collaborative learning in which they conclude that group processes played a central role, but they did not have detailed, continuous interaction data to explore how these processes actually unfolded. They only had data to demonstrate that there was a change between two time instances that they analyzed (e.g., Barron, 2003; Kapur & Kinzer, 2009; Schwartz, 1995), and they had to speculate about intervening group-cognitive processes.

A longitudinal study of dynamic geometry (Stahl, 2016) involved a sequence of eight hour-long sessions, each with a geometry figure to manipulate, discuss and construct. The collaboration environment included a shared workspace with a geometry application that restricted manipulation of points, lines and figures based on how they were constructed. There were sample figures to manipulate, textual instructions to guide the session and a chat interface for group communication. The tasks for the sequences of sessions were carefully planned—based on previous mathematical experience and numerous trials—to encourage the accumulation of specific group practices. Group practices had to be established in roughly this order:

- Be able to use the computer and the collaboration environment.
- Be able to communicate in chat, repair mistakes and misunderstandings, propose actions.
- Use the dynamic-geometry app; find menu options; create points, lines and figures.
- Drag geometric objects to observe their behavior.
- Construct figures so they would embody desired constraints or dependencies.
- Discuss why a geometric figure behaved the way it did (argumentation, explanation, proof).

Using the methods discussed in this chapter, researchers were able to identify when groups adopted practices such as these, what difficulties they encountered and when they failed to establish these practices.

Design: Orchestrating Group Practices

CSCL is not a standalone educational approach. Collaborative learning is not always the best approach, and it is usually more effective when combined with complementary approaches in ways that take into account the interactions among the individual, small-group and community levels of description. However, collaborative learning can be uniquely effective in introducing important practices.

In a school context, a teacher may orchestrate CSCL sessions to fit into a sequence of varied learning modes. Perhaps an introductory presentation by the teacher will motivate a new topic. Then individual reading might provide background information. At that point, collaborative exploration can lend a creative and interactive process of discovery, supported by discussion and sociability. Perhaps a homework assignment would open an opportunity for students to adopt recent group practices as their own individual behaviors. The topic could conclude with a class discussion session and an individual writing of reflections. The written reflection could also be shared with group members, perhaps leading to a group position paper on the topic. Acquired group practices could thereby influence individual and classroom learning.

Technology: Supporting Group Practices

Computer support for multiple modalities can be used to support specific group practices. For instance, generic text chat or discussion forums can support argumentation, but there can also be designed affordances of special CSCL argumentation environments that foster negotiation or analysis of argumentation structure (Schwarz & Baker, 2017). Pointing and other graphical manipulation tools can represent references from one screen icon to another (Mühlpfordt & Wessner, 2009). Eye-tracking displays can enhance joint attention by indicating where each participant is looking (Schneider & Pea, 2013).

A shared workspace can be important for providing a "joint problem space" (Teasley & Roschelle, 1993) and acting as a group memory that can even bridge discontinuities in group presence (Sarmiento, 2007; Sarmiento & Stahl, 2008). The workspace can be taken a step further with simulations or modeling, as with VMT's dynamic-geometry app or Roschelle's model of acceleration.

Methodology: Analyzing Group Practices

The analytic methodology presented in this chapter offers the CSCL researcher a way to discover and document the adoption of group practices as a dynamic view into collaborative learning. Importantly, this view can guide on-going design iterations.

The analysis of group practices opens up a contemporary approach to designing and assessing education. Group practices stand at the center of collaborative learning, which is foundational for human learning.

Additional Reading

(Medina et al., 2009) ***Representational Practices in VMT*** analyzes the adoption of several group practices by a team of students discussing geometry problems.

(Stahl, 2020) - ***Theoretical Investigations*** brings together many of the past articles in the *International Journal of CSCL* and recent essays by the journal editor that are most relevant to this chapter. Together, they point in the direction of CSCL theory indicated here for the future.

(Stahl, 2016) ***Constructing Dynamic Triangles Together*** follows the collaborative learning of a team of three girls longitudinally over eight weeks as they begin to learn dynamic geometry. The book identifies about 60 group practices that the team adopts.

(Stahl, 2013) ***Translating Euclid*** presents multiple perspectives on the Virtual Math Teams project. It includes the first analysis of the adoption of a group practice more fully discussed in the preceding reference.

(Stahl, 2006) ***Group Cognition*** provides the initial discussion of group cognition as a central concept for analyzing CSCL interactions. The idea of group cognition arose in the writing of this book and led to the focus on group practice a decade later.

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4. Curriculum for CSCL

Abstract: The Coronavirus pandemic has thrown public schooling into crisis, trying to juggle shifting instructional modes: classrooms, online, home-schooling, student pods, hybrid and blends of these. This poses an urgent need to redesign curriculum using available technology to implement approaches that incorporate the findings of the learning sciences, including the emphasis on collaborative learning, computer mediation, student discourse and embodied feedback. This paper proposes a model of such learning, illustrated using existing dynamic-geometry technology to translate Euclidean geometry study into collaborative learning by student pods. The technology allows teachers and students to interact with the same material in multiple modes, so that blended approaches can be flexibly adapted to students with diverse preferred learning approaches or needs and structured into parallel or successive phases of blended learning. The technology can be used by online students, co-located small groups and school classrooms, with teachers and students having shared access to materials and to student work across interaction modes.

Keywords: dynamic geometry; group practices; CSCL, group cognition, learning pods.

Introduction: Student Pods during the Pandemic

Alternatives to the traditional teacher-centric physical classroom suddenly became necessary during the coronavirus pandemic to cover a variety of shifting learning options at all age levels. Although the creation of student "pods" (small groups of students who study together) was popularized as a way of restricting the spread of virus, it was rarely transferred to the organization of online learning as collaborative learning.

Research in the learning sciences has long explored pedagogies and technologies for student-centered and collaborative learning (Sawyer, 2021). However, the prevailing practice of schooling has changed little (Sinclair, 2008); students, parents, teachers, school districts and countries were poorly prepared for the challenges of the pandemic. Case studies from countries around the world documented the common perceptions by students, teachers and administrators of inadequate infrastructure and pedagogical preparation for online learning (Noor, Isa & Mazhar, 2020; Peimani & Kamalipour, 2021).

An abrupt rush to online modes found that the digital divide that leaders had promised to address for decades still left disadvantaged populations out (Blume, 2020; Preez & Grange, 2020). Income inequality by class and nation correlates strongly with lack of computer and Internet access. In addition to confronting these hardware issues and low levels of computer training, teachers everywhere had access to few applications designed to support student learning in specific disciplines. They had to rely on commercial business software like Zoom and management systems like Blackboard, which incorporated none of the lessons of learning-sciences research.

While school districts planned for "reopening," administrators prepared scenarios for combining in-class, online, home schooling and small student pods. The plans kept shifting and little was done to prepare and support teachers to teach in these various combinations of modalities. Moreover, teachers were rarely guided in redesigning their curriculum for online situations, in which they were often neither trained nor experienced.

Pundits and early surveys were quick to call the attempt to teach online a failure and declare that it simply highlighted how important social interaction was to students. They argued that online media severely reduced student motivation by removing inter-personal interaction (Niemi & Kousa, 2020; Tartavulea et al., 2020).

However, the field of computer-supported collaborative learning (CSCL) has always emphasized the centrality of social interaction to learning, demonstrating that sociality could be supported online as well as face-to-face (Cress, Rosé, Wise & Oshima, 2021; Stahl, Koschmann & Suthers, 2021). Micro-analyses of knowledge building in CSCL contexts detail the centrality of social interaction to effective online collaborative learning and even the students' enjoyment of the online social contact (Stahl, 2021). The source of asocial feelings is the restriction of online education to simply reproducing teacher lectures and repetitive individual drill. It is necessary to explicitly support social contact and interaction among students to replace the subtle student-to-student contact of co-presence. This can be done through collaborative learning, which simultaneously maintains a focus of the interaction on the subject matter.

The pandemic forced teachers to suddenly change their teaching methods and classroom practices, as reported by (Johnson, Veletsianos & Seaman, 2020). The sudden onset of pandemic conditions and school lockdown made it infeasible to introduce new technologies, let alone scale up research prototypes for widespread usage. Nevertheless, the lessons of the pandemic should lead over the longer run to more effective online options, as well as preparation in terms of infrastructure, support, attitude and skills for innovative online educational approaches and applications (Adedoyin & Soykan, 2020).

In the face of the pandemic, teachers and school districts were largely on their own to adapt commercially established technologies like Zoom and Blackboard to changing local circumstances. One innovative example was an attempt to make teacher presentations in Blackboard more interactive by instituting a hybrid audience of some students in class (to provide feedback to the teacher) and others online (Busto, Dumbser & Gaburro, 2021). Other researchers stressed the need to go further and introduce an intermediate scale between the individual students and the teacher-led classroom—namely a student-centered small-group or pod learning unit (Orlov et al., 2020). The following provides an example of how a careful integration of existing technologies (Zoom or Blackboard with GeoGebra) can support pod learning and blend the online with in-class as well as the small group with whole classroom.

This article describes how a research project (Virtual Math Teams, or VMT) translated the ancient pedagogy of Euclidean geometry into a model of CSCL, and how that was then further redesigned to support blended-learning pedagogy for pandemic conditions (with GeoGebra Classes). This can serve as a prototype for the blended teaching of other subjects in mathematics and other fields. If such a model can succeed during the pandemic, it can herald on-going practical new forms of education for the future. The pandemic experience will change schooling to take increased advantage of online communication and offers an opportunity for CSCL to guide that process in a progressive direction. The approach described here using GeoGebra Classes with VMT curriculum can be implemented immediately, during the pandemic, and then further developed later for post-pandemic blended collaborative learning.

Designing for Virtual Math Teams

The VMT research project was conducted at the Math Forum at Drexel University in Philadelphia, USA from 2004 through 2014. The VMT research has been documented in five volumes analyzing excerpts of actual student interaction from a variety of viewpoints and methodologies (Stahl, 2006; 2009; 2013; 2016; 2021).

The project was an extended effort to implement and explore a specific vision of computer-supported collaborative learning (CSCL), applied to the learning of mathematics:

- First, it generated and collected data on small online groups of public-school students collaborating on problem solving.
- Second, it provided computer support, including a shared whiteboard and a dynamic-geometry app.
- Third, it analyzed the group interaction that unfolded in the team discourse.
- Fourth, it elaborated aspects of a theory of “group cognition” (Stahl, 2006). Several papers published during this period and contributing to the broad vision of CSCL have now been reprinted and reflected upon

in *Theoretical Investigations: Philosophic Foundations of Group Cognition* (Stahl, 2021). Several chapters in this volume analyze aspects of group cognition based on excerpts of student discourses during VMT sessions.

The VMT project cycled through many iterations of design-based research (design, trial, analysis, redesign), developing an online collaboration environment for small groups of students to learn mathematics together. The eleven chapters of (Stahl, 2013) describe the project from different perspectives: the CSCL vision; the history, philosophy, nature and mathematics of geometry; the theory of collaboration; the approach to pedagogy, technology and analysis; the curriculum developed; and the design-based character of the research project. The theory of group cognition provides a framework for pod-based education by describing how knowledge building can take place through small-group interaction—with implications for conceptualizing collaborative learning, designing for it, analyzing group-learning processes/practices and assessing its success. The theory explores the inter-weaving of individual, group and classroom learning.

The VMT software eventually incorporated GeoGebra,[1] an app for dynamic geometry, which is freely available and globally popular (available in over a hundred languages). Dynamic geometry is a computer-based version of Euclidean geometry that allows one to construct figures with relationships among the parts and then allows the constructed points to be dragged around to test the dependencies—providing immediate visual feedback (Hölzl, 1996; Jones, 1996; Laborde, 2000).

As part of the VMT Project, curricular units were designed and tried out in online after-school settings (primarily in the Eastern USA), with teacher training on how to guide the student groups and how to integrate and support the online collaborative learning with teacher presentations, readings, homework and class discussion (Grisi-Dicker, Powell, Silverman & Fetter, 2012). The geometry activities provided hands-on experience exploring the basics of dynamic geometry in small-group collaboration. Student peer discussion was encouraged that would promote mathematical discourse and reflection (Sfard, 2008). In this way, the research project translated Euclid's curriculum into the computer age. Euclid's *Elements* (Euclid, 300 BCE), which had inspired thinkers for centuries, was reworked in terms of dynamic geometry and a learning-sciences perspective (Sinclair, 2008).

[1] https://www.geogebra.org

Redesigning for Pandemic Pods with GeoGebra Classes

The VMT platform was no longer available when the pandemic appeared and made the need for supporting online learning particularly urgent. While teachers and students can download GeoGebra without VMT, that would not support full collaboration, where several students can work together on a shared geometric figure. Fortunately, GeoGebra recently released a "Class" function, in which a teacher can invite several students (a pod) to work on their own versions of the same construction, and the teacher can view each student's construction work and discussion in a Class dashboard (Figures 1 and 2). The dashboard provides a form of "learning analytics" (Cress et al., 2021) support for the teacher, which can also be adapted to facilitate student collaboration.

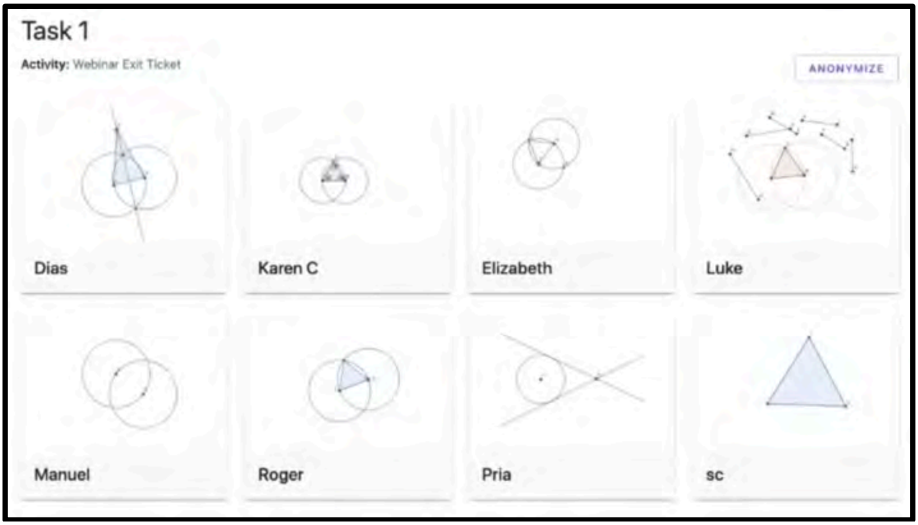

Figure 1. The GeoGebra Class dashboard displays the current state of each student's work on a selected task. In this example, the students are learning Euclid's construction of an equilateral triangle.

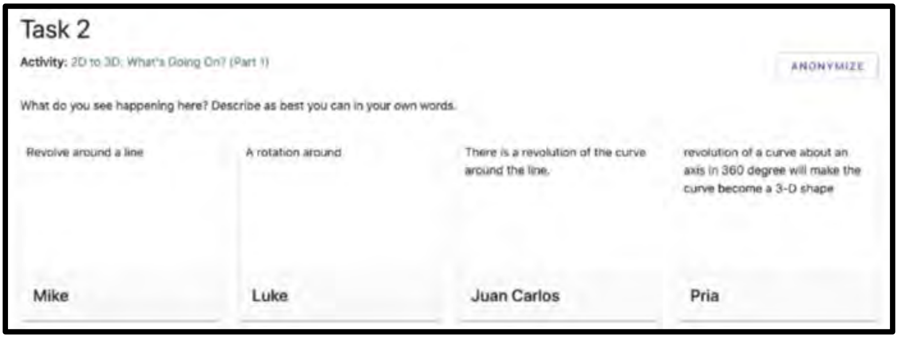

Figure 2. The GeoGebra Class dashboard also displays each student's response to selected questions. In this example the students are discussing rotating a 2-D curve into the 3rd dimension.

To take advantage of GeoGebra Classes, VMT's dynamic-geometry curriculum has now been adapted to small pods or even home-schooled individual students using the Classes functionality. The new curriculum is called *Dynamic Geometry Game for Pods* (Stahl, 2020). Using a set of 50 GeoGebra activities that cover much of basic high-school or college geometry, the instructions and the reflection questions were reworked for the new scenario (Figures 3 and 4). The sequencing of tasks was maintained from VMT, which roughly followed Euclid's (300 BCE) classic presentation as well as contemporary U.S. Common Core guidelines for geometry courses (National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010).

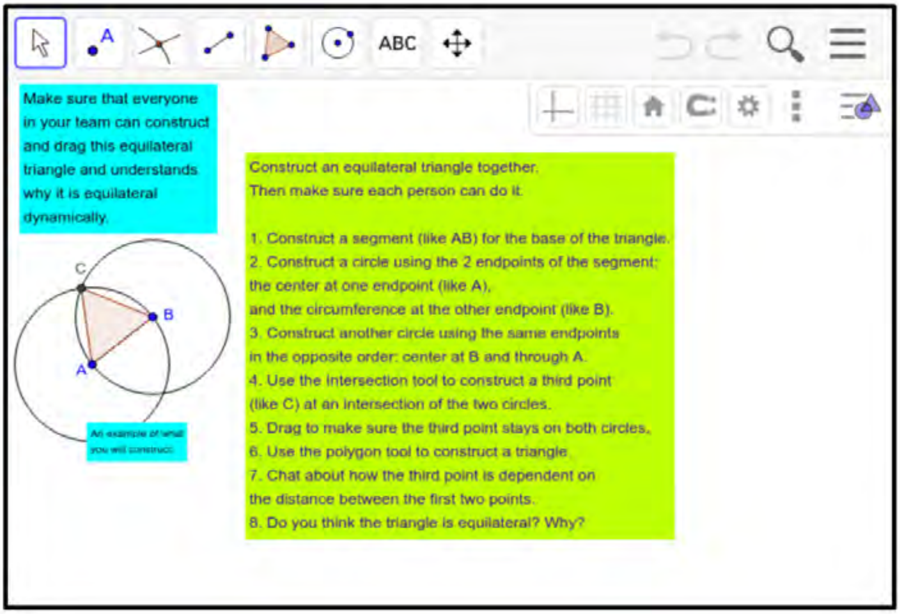

Figure 3. One of 50 tasks for student pods: Euclid's construction of an equilateral triangle.

Questions.

Did you construct your own equilateral triangle?

Did you use the DRAG TEST to make sure it works properly?

The equilateral construction opens up the world of geometry; if you understand how it works deeply, you will understand much about geometry.

In geometry, a circle is defined as the set of points that are all the same distance from the center point. So every radius of a certain circle is the same length.

Drag each point in your triangle and discuss how the position of the third point is dependent on the distance between the first two points.

Is your triangle equilateral (all sides equal and all angles equal)?

Figure 4. A set of reflection questions for members of pods to discuss related to the task in Figure 3.

The revised curriculum is available on the GeoGebra repository site as an interactive GeoGebra book.[2] Additionally, a free e-book is available so people can conveniently

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[2] https://www.geogebra.org/m/vhuepxvq#material/swj6vqbp.

review the curriculum offline (Stahl, 2020). The book's introductions guide classroom teachers, home-schooling parents, pod tutors or self-guided students to use the curriculum. The format is that of a game with successively challenging levels, which must be conquered consecutively. It is structured as a sequence of five parts, each including about 10 of the hour-long curricular activities, grouped by geometry level and degree of expertise required. The game levels are: (1) beginner, (2) construction, (3) triangles, (4) circles, (5) dependency, (6) compass, (7) congruence, (8) inscribed polygons, (9) transformation, (10) quadrilaterals, (11) advanced geometer, (12) problem solver and (13) expert.

The ideal usage would be by pods of students working online and communicating through the dashboard. A pod coordinator or teacher can provide all participants with access to the real-time dashboard, so that everyone can observe and discuss what everyone else is doing in GeoGebra and typing in the Class interface. Furthermore, GeoGebra can be shared in Zoom, to provide spoken interaction and recording of sessions for student reflection, teacher supervision or researcher analysis.

Note that the Class functionality is not fully collaborative, even when all students have access to the dashboard. Each student works in their own construction area (Figure 1), unlike the shared workspace of the VMT software (Figure 3). Also, each student answers the reflection questions in their own window (Figure 2), rather than in a chat window as in VMT. However, at least the students can see each other's work and learn from it. Also, if GeoGebra is embedded in Zoom, then the students can discuss their approaches together. The limited support for collaboration is a trade-off of using established software for innovative pedagogy.

The goal is that math teachers and others can adapt the use of this curriculum and technology to diverse and rapidly changing teaching conditions and learning modalities. If used with full online access—including the Class dashboard shared by everyone, possibly embedded in Zoom—the collaborative learning experience can approach that envisioned in the VMT research. However, it can also be used in other ways and across various presentation modalities of blended approaches. Student work carried out individually can be shared within a Class pod and then presented in a whole classroom setting, whether virtual or face-to-face.

The usage of GeoGebra in a collaborative online session can provide all students with hands-on experience in geometry construction and investigation (manipulation and reflection). A major advantage of collaborative learning is that students can help each other, pooling their partially developed skills and understanding. However, it is also important for teachers to provide introductions to new ideas and to review in the classroom context the work that students are doing in pods or individually. Furthermore, individual students must make sense of the material for themselves; reading and working individually on problems is important to support collaborative learning. That is why teachers should orchestrate blended learning, incorporating individual, small group and classroom learning in a coordinated, mutually supportive way. Of course, students learn best in diverse ways, so it is productive to offer them alternative educational modalities. Teachers can adapt and mix the modalities in response to local circumstances and learning differences among their students.

Findings from VMT Trials

The VMT Project was conceived and executed as extended design-based research (DBR), as detailed in (Stahl, 2013). This involved innovations in technology, pedagogy, assessment and theory. Each aspect of the VMT Project has been reviewed in multiple formats and contexts by international researchers from relevant disciplines.

Findings from the project have been discussed in about 250 publications, including peer-reviewed workshops, conference papers, journal articles, dissertations and books. The project evolved over a decade, prototyping and testing technologies and curricula that underwent multiple iterative revisions each year. The current curriculum for blended learning, *Dynamic Geometry Game for Pods,* is the latest iteration, moving from the VMT software platform to the GeoGebra Class function to support blended learning including collaborative learning in online student pods.

Although a variety of analysis approaches were applied to identify successes and problems during VMT trials, most of the published analyses used a form of conversation analysis adopted from informal conversation to the interaction of online school mathematics. While most of the analyses focused on brief interactions among small groups of students, some included longer sequences, sometimes spanning multiple sessions. For instance, the entire interaction of a group of three middle-school girls—the "Cereal Team"—was followed longitudinally across eight hour-long online sessions and was subjected to detailed micro-analysis of all the discourse and geometry construction (see Stahl, 2013, Chapter 7; 2016).

As suggested by the title of (Stahl, 2013), *Translating Euclid: Designing a Human-Centered Mathematics*, the pedagogy was converted away from expecting students to accept and memorize concepts, theorems and techniques based on authority. Instead, the project promoted a student-centered and inquiry-based approach of exploration, feedback and discourse based on situated and embodied interaction with computer-based artifacts and guided discussion practicing the use of mathematical terminology.

Although the VMT Project was originally intended to investigate and document phenomena of *group cognition* (Stahl, 2006), in the end it proposed a methodological focus on *group practices* (Stahl, 2016). The sequencing of challenges in the *Dynamic Geometry Game for Pods* is carefully designed to guide student groups and individuals to adopt group practices and individual skills needed to progress through the process of collaboratively learning dynamic geometry. For instance, procedures for placing lines, dragging points, constructing circles and checking connections among objects are practiced before more complex constructions are proposed, which rely on these skills. The VMT research indicates that such an approach can be effective without being overly directive if a group of students can explore and discuss each technique collaboratively. The *Dynamic Geometry Game for Pods* is based on this body of findings, as well as on the extensive learning-science literature that underlies the VMT project's theory of group cognition, reviewed in (Stahl, 2021).

Supporting Group Practices in Blended Learning

Teachers, parents and pod organizers can now use the GeoGebra book with its 50 challenges for courses in high-school geometry. Educators in other fields could follow this example and develop analogous curriculum and technology usage. Then the results of such educational interventions could be collected, shared and analyzed. Analysis techniques honed during the VMT Project (Medina & Stahl, 2021) could be used along with other methods to investigate collaboration patterns in interaction discourse, the adoption of targeted group practices and advancement of learning goals.

This approach contrasts with the view of learning as primarily a psychological process of changing an individual's mental contents or cerebral representations (Gardner, 1985; Thorndike, 1914). Rather, individual learning is seen as largely a result of group and social processes or practices in which multiple people, artifacts, technologies and discourses interact to evolve cognitive products at the group level, such as geometric constructions, informal proofs, group reports and textual responses to questions (Stahl & Hakkarainen, 2021). Such group products require the establishment and maintenance of mutual understandings, intersubjectivity, distributed cognition, communal conceptualizations, common interpretations of problems, collaborative problem solving and shared knowledge. While individuals contribute to these group phenomena, the collective products have a life of their own (Latour, 1996; 2008; Lave & Wenger, 1991; Tomasello, 2014; Vygotsky, 1930; 1934/1986).

One way that group cognition can result in individual learning is through the adoption of *group practices*, which then provide models for individual behavior (Stahl, 2021, Chapter 16). For instance, a pod of students working on a geometry problem can encounter a concept, theorem or technique that may originate with a pod member, from the problem description or from the history of geometry. The pod discussion may then explicitly discuss what was encountered, come to a shared understanding of how it applies to the pod's current situation and even overtly agree to use it. In subsequent interactions, the pod simply applies the new practice without discussing it again. It becomes a tacit group practice, recognized by everyone in the pod. Pod members may also retain this practice as their own individual mathematical skill when they work outside the pod.

While the theory of group cognition and group practice has been discussed at length in the reports of the VMT Project, it will be interesting to see how these theories are manifested in new situations in which the *Dynamic Geometry Game for Pods* or analogous curricula are enacted. In addition to these quite broad theories, the VMT Project developed characteristics that may be more specific to digital geometry. It will be important to investigate the applicability of these features in new contexts and disciplines.

A central focus of the *Dynamic Geometry Game for Pods* is on the practices involving *dependency* as central to dynamic-geometric constructions. For instance, in constructing an equilateral triangle with radii of equal circles, it is essential that the lengths of the three sides are dependent upon the equal radii, even when a triangle vertex or a circle center is dragged to a new location. Indeed, the proof that the triangle is equilateral hinges on this dependency—and has for thousands of years since Euclid (300 BCE). Viewing constructions in terms of practices that establish and preserve dependencies (rather than in terms of visual appearance or numeric measurements) is quite difficult for students to learn. One can observe such an insight as it emerges in the discourse of a pod, assuming that the curriculum has been effectively designed to promote such a group practice.

One aspect of curriculum design to support the adoption of specific group practices in dynamic geometry is to sequence tasks and associated practices carefully. This is clear in Euclid's carefully ordered presentation and in the hierarchies of theorems in every area of mathematics.

However, in collaborative learning of geometry, groups must adopt more practices than just the purely mathematical ones. Specifically, the micro-analysis of the eight sessions of the Cereal Team identified about sixty group practices that the group explicitly, observably enacted. These practices successively contributed to various core aspects of the group's abilities: to collaborate online; to drag, construct, and transform dynamic-geometry figures; to use GeoGebra tools; to identify and construct geometric dependencies; and to engage in mathematical discourse about their accomplishments.

Table 1 lists practices explicitly discussed by the Cereal Group and identified in the analysis of their discourse (Stahl, 2016). Each of these practices is illustrated in the commentary on the detailed transcript of the student group's interaction. One can see the group negotiating, adopting and reusing each group practice in the context of their mathematical problem solving and online collaborative learning.

Table 1. Identified practices adopted by the Cereal Group.

Group collaboration practices:

- Discursive turn taking (responding to each other and eliciting responses).
- Coordinating activity (deciding who should take each step).
- Constituting a collectivity (e.g., using "we" rather than "I" as agent).
- Sequentiality (establishing meaning by temporal context).
- Co-presence (being situated together in a shared world of concerns).
- Joint attention (focus on the same, shared images, words and actions).
- Opening and closing topics (changing discourse topics together).
- Interpersonal temporality (recognizing the same sequence of topics, etc.).
- Shared understanding (common ground).
- Repair of understanding problems (explicitly fixing misunderstandings).
- Indexicality (referencing the same things with their discourse).
- Use of new terminology (adopting new shared words).
- Group agency (deciding what to do as a group).
- Sociality (maintaining friendly relations).
- Intersubjectivity (sharing perspectives).

Group dragging practices:

- Do not drag lines to visually coincide with existing points, but use the points to construct lines between or through them.
- Observe visible feedback from the software to guide dragging and construction.
- Drag points to test if geometric relationships are maintained.
- Drag geometric objects to observe invariances.
- Drag geometric objects to vary the figures and see if relationships are always maintained.
- Some points cannot be dragged or only dragged to a limited extent; they are constrained.

Group construction practices:

- Reproduce a figure by following instruction steps.
- Draw a figure by dragging objects to appear right.
- Draw a figure by dragging objects and then measure to check.
- Draw a figure by dragging objects to align with a standard.
- Construct equal lengths using radii of circles.

- Use previous construction practices to solve new problems.
- Construct an object using existing points to define the object by those points.
- Discuss geometric relationships as results of the construction process.
- Check a construction by dragging its points to test if relationships remain invariant.

Group tool-usage practices:

- Use two points to define a line or segment.
- Use special GeoGebra tools to construct perpendicular lines.
- Use custom tools to reproduce constructed figures.
- Use the drag test to check constructions for invariants resulting from custom tools.

Group dependency-related practices:

- Drag the vertices of a figure to explore its invariants and their dependencies.
- Construct an equilateral triangle with two sides having lengths dependent on the length of the base, by using circles to define the dependency.
- Circles that define dependencies can be hidden from view, but not deleted, and still maintain the dependencies.
- Construct a point confined to a segment by creating a point on the segment.
- Construct dependencies by identifying relationships among objects, such as segments that must be the same length.
- Construct an inscribed triangle using the compass tool to make distances to the three vertices dependent on each other.
- Use the drag test to check constructions for invariants.
- Discuss relationships among a figure’s objects to identify the need for construction of dependencies.
- Points in GeoGebra are colored differently if they are free, restricted or dependent.
- Indications of dependency imply the existence of constructions (such as regular circles or compass circles) that maintain the dependencies, even if the construction objects are hidden.
- Construct a square with two perpendiculars to the base with lengths dependent on the length of the base.
- Construct an inscribed square using the compass tool to make distances on the four sides dependent on each other.

- Use the drag test routinely to check constructions for invariants.

Group practices using chat and GeoGebra actions:

- Identify a specific figure for analysis.
- Reference a geometric object by the letters labeling its vertices or defining points.
- Vary a figure to expand the generality of observations to a range of variations
- Drag vertices to explore what relationships are invariant when objects are moved, rotated, extended.
- Drag vertices to explore what objects are dependent upon the positions of other objects.
- Notice interesting behaviors of mathematical objects
- Use precise mathematical terminology to describe objects and their behaviors.
- Discuss observations, conjectures and proposals to clarify and examine them.
- Discuss the design of dependencies needed to construct figures with specific invariants.
- Use discourse to focus joint attention and to point to visual details.
- Bridge to past related experiences and situate them in the present context.
- Wonder, conjecture, propose. Use these to guide exploration.
- Display geometric relationships by dragging to reveal and communicate complex behaviors.
- Design a sequence of construction steps that would result in desired dependencies.
- Drag to test conjectures.
- Construct a designed figure to test the design of dependencies.

The design of curriculum for collaborative or blended learning can be motivated by the goal of promoting the adoption of specific group practices. The curriculum can, for instance, scaffold collaboration practices like turn taking to get all students in a group involved. Then it can support discourse practices to help groups make their meanings explicit and shared.

Some of the listed group practices are specific to the collaborative learning of dynamic geometry with GeoGebra. Many are generally supportive of productive collaborative interaction and discourse. Each subject area will have its own central practices to be supported and mastered, as well as the more universal ones. It is instructive to see the special demands of dynamic geometry. In addition to the focus on construction of dependencies and the associated discourse of how different elements of a figure are dependent upon each other, the use of GeoGebra introduces further specific challenges. For instance, it was necessary to design the VMT technology to allow all group members to observe each other's construction sequences in detail as they unfolded in real time in the app, because the animation of those processes could be quite informative (Çakir, Zemel & Stahl, 2009). In addition, the immediate feedback afforded by GeoGebra—for instance when someone dragged a point and the whole construction changed, revealing what was and what was not dependent on that point—was crucial for group behavior, discourse and learning.

Broadening the Model for Blended Learning

The proposed use of GeoGebra Classes illustrates the adaption of existing technology to an educational innovation explored in research using a prototype that is not available for widespread use during the pandemic. While the GeoGebra Classes functionality does not fully support small groups to share a workspace for exploring geometric construction, it does provide an available platform for student pods working within a teacher-led classroom. Students in a pod can see each other's work in real time and can reflect upon it by answering questions that are integrated into the curriculum. The teacher can also follow all the student work and discourse and display this within a classroom context. Thus, blended learning is supported with online GeoGebra, individual construction and reflection, small-group interaction and classroom presentation and discussion. The latest version of the online VMT curriculum is fully incorporated in a motivational game-challenge format. Optionally, the GeoGebra Class can be embedded in Zoom or Blackboard to support additional online and blended functionality.

The research that lies behind the VMT curriculum resulted in enumeration of group practices that are important to support for collaborative learning in its subject domain of dynamic geometry. Research reports developed the theory of group cognition, which describes how small groups can build knowledge collaboratively, in orchestration with individual learning and classroom instruction. They analyzed in considerable detail the nature of online mathematical discourse and problem solving, including how to support and analyze it.

These features of the VMT experience will need to be reconsidered in the design and analysis of support for blended learning in other subject areas, particularly to the extent that curriculum and technology diverge from dynamic geometry and GeoGebra. Just as the VMT project focused its curriculum on geometric dependencies as central to mastering dynamic geometry, efforts in other disciplines may target concepts that underlie their subjects, much as Roschelle's (1996) early CSCL physics support app targeted the understanding of acceleration as core to learning Newtonian mechanics or an algebra curriculum might revolve around the preservation of equalities.

Dynamic geometry is just one area of mathematics covered by GeoGebra. The software supports all of school mathematics from kindergarten through junior college. It is available in over a hundred world languages. Thus, a teacher, parent or student who masters dynamic geometry through the curriculum discussed here can go on to explore other areas of mathematics with this kind of computer support. Learning scientists can develop curriculum units for all ages in all countries following the model illustrated here by the *Dynamic Geometry Game for Pods*.

This is not to say that all instruction should be provided in a CSCL format. Collaboration can be particularly productive for exploring problems that are somewhat beyond the reach of individual students. Also, small-group collaborative learning is most effective in sessions that are *orchestrated* into sequences of individual, group and classroom activities that support each other (Dillenbourg, Nussbaum, Dimitriadis & Roschelle, 2013; Stein, Engle, Smith & Hughes, 2008). Blended learning approaches can supplement collaborative learning with complementary instructional modes. For example, a teacher presentation and student readings can precede online peer interaction, which is followed up by classroom discussion and reporting. While teachers struggle to find effective approaches in flipped, hybrid and online classes, there is now a clear opportunity for moving CSCL ideas into widespread practice. Exploration of pod-based learning during the pandemic could lead to important innovations in post-pandemic blended, collaborative and online learning.

It is difficult to convert courses from in-class to online. Typically, much of the effort goes into designing the curriculum and student tasks in advance and instituting new procedures and expectations for the students. A culture of collaboration must be established in the classroom over time. For instance, grading should be redefined in terms of group participation and team accomplishments. It takes several iterations to work things out; in each course, it requires teacher patience while students adjust. Students must be guided to communicate with their collaborators and to let go of competitive instincts.

The model proposed here is not a panacea for the current crisis of schooling, but rather an indication of a potential direction forward, for the remainder of the pandemic and beyond. We need to overcome the digital divide, promote collaborative learning, develop educational technology for exploring many domains, train teachers in online teaching, redesign curriculum to make it flexible for shifting modes of schooling. If we do not do this, then the learning sciences will have missed an opportunity to promote new forms of collaborative, inquiry-based and computer-supported learning. Only by meeting this challenge can we avoid the looming destruction of public education and the resultant serious worsening of social inequity.

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5. Technological Artifacts

Martin Heidegger's exploration of how things are disclosed (his ontology, or philosophy of being) provides innovative ways of understanding many phenomena, including works of art. Although Heidegger did not write about music, he did discuss the working of other art forms, including painting, pottery and sculpture. To discuss the implications of Heidegger's philosophy for understanding the nature of music, we can consider his analyses of these different art forms and adapt them to music. This chapter will extend Heidegger's approach to art by applying it to the development of electronic music in the mid-twentieth century to elucidate both his philosophy and that intriguing movement in music.

Heidegger is concerned with the way things come into being, their forms of being, or how their being is worked out. The *being* of something centrally involves how it presents or discloses itself in its specific form of appearance. This chapter will explore the being of works of a certain genre of music, *e-music*—that is, how works of electronic music are structured to disclose worlds of sound in certain ways.

The term "e-music" is here coined to refer to a spirit of electronic music as it developed in the 1950s and 1960s (Dunn, 1992; Eimert, 1957). E-music grew out of the serial music of Schoenberg and others, and featured composers such as Varese, Stockhausen, Boulez and Xenakis. It had broad influences on classical, jazz, fusion, acid rock, rap, new-age trance and disco-dance music. Integral to e-music's compositional experimentation was the concomitant development of analog and digital technologies of sound production, including tape splicing, sound sampling, sequencers and synthesizers. We will consider e-music specifically as exemplified by paradigmatic works and reflections of Karl-Heinz Stockhausen (1962; 1972), which defined an approach to composition with striking parallels to Heidegger's philosophy.

We will view the being of works of e-music from the perspectives of four identifiable approaches by Heidegger to analyzing how works of art and other beings are disclosed:

(a) Available beings like tools are disclosed as *understood* within the nexus of beings that form one's world as one pursues human concerns. (Heidegger, 1927/1996)
(b) Works of art like paintings disclose by setting truth into work—i.e., disclosing a *world* created by the working of the artwork. (Heidegger, 1935/1964)
(c) Things like hand-crafted jugs are disclosed in accordance with their historic *epoch* of being, such as the antique, medieval, mechanical or digital era. (Heidegger, 1962/1972)
(d) Works like sculpture disclose relations of *form, space and time*—thereby creating material, moments and places for people to dwell. (Heidegger, 1969/1973)

We will explore how to apply each of these four ontological approaches to works of music through an investigation of e-music as it emerged in the 1960s. The following characteristics of e-music relate to Heidegger's philosophy:

(a) E-music illustrates how one hears already *understood* sounds versus noise.
(b) Works of e-music open sonic *worlds* in which novel aural phenomena are set into work.
(c) E-music is produced with innovative *technologies*—such as the use of digital synthesizers or computers to manipulate sound parameters—which are explored by e-music compositions.
(d) Works of e-music establish relations of *form, space and time* among sounds through the explicit, controlled composition of these dimensions.

While Heidegger offers a transformative way of viewing art, his conception of historical change is open to critique. In addition to illustrating the power of Heidegger's innovative insights, we will also note their limitations—primarily from the viewpoint of Marx's socio-historical philosophy, which Heidegger failed to appreciate (Habermas, 1992; Stahl, 1975):

(a) Heidegger's view of authentic man is ideological and individualistic, while his analysis of tools like e-music technologies downplays their ties to modes of production and consumption. (Adorno, 1964/1973)
(b) Heidegger's analysis of art ignores the complexity of the labor involved in making a film, a jug or a musical composition, and how that work is socially and historically mediated. (Benjamin, 1936/1969)
(c) Heidegger's account of history ignores its social structuration, whereby history is not just given, but is produced, reproduced and transformed by works, including works of music. (Bourdieu, 1972/1995; Giddens, 1984)
(d) Heidegger's characterization of sculpture imposes his conceptualizations of space and time, rather than developing them from how they are disclosed in the work of sculptors and composers. (Mitchell, 2010)

Heidegger sees the working of the work of art as the revelation of truth. Marxists see the production of art as creative labor mediated by technological means and social processes. Although neither Heidegger nor Marx explicitly considered music at length, analysis of the technology and history of e-music can provide increased understanding of the insights and the limitations of both philosophies. The following sections discuss e-music and other art forms from the perspectives of Heidegger's four successive approaches to the being of artworks, raising concerns about the adequacy of those views. Examples from the development of e-music—and related observations from painting, pottery and sculpture—are used to extend Heidegger's philosophy. These instances should render Heidegger's abstruse ontological theories more tangible and comprehensible, as well as suggest how aspects of the production process and socio-historical context should be incorporated in the origin of the being of works of art.

(a) Beings in the World

Heidegger's most important publication—which argued for the need to understand the being of beings in terms of how they are disclosed—was *Being and Time* (Heidegger, 1927/1996). Here he rejected the traditional view that people exist within an objective, value-free environment, surrounded by material objects upon which they impose meanings. In contrast, he proposed that human existence discloses a network of meaningful beings, whose significance is tentatively suggested from the start in terms of one's concerns, expectations and pre-judgments. The world around us is always already understood; Heidegger's analysis is a philosophy of just how the world is pre-interpreted—and how this understanding may subsequently be made explicit and further articulated (Stahl, 1975; 1993).

Heidegger illustrates the pre-understanding of the world in terms of how we hear sounds:

> Initially we never hear noises and complexes of sounds, but the creaking wagon, the motorcycle. We hear the column on the march, the north wind, the woodpecker tapping, the crackling fire. It requires a very artificial and complicated attitude in order to "hear" a "pure noise." (Heidegger, 1927/1996, S. 163/p. 153; see also Heidegger, 1935/1963, S. 15/p. 656)[3]

In perceiving a sound, we immediately understand it *as* something, as the sound of a certain object, instrument or process, or as a certain kind of sound.

This can be directly applied to how we hear music. We do not first or primarily hear music as uninterpreted raw sounds that we must then interpret. Rather we hear the bowing of a violin, the ringing of a bell, the strumming of a guitar. We hear the solemnity of a requiem, the joy of a jig or the romance of a love song. We may also hear the expressive communication of a performer or the emotional intention of a composer. According to Heidegger, these initial forms of being of the sounds are determined by our culture, by how "one" interprets them. Once something is initially disclosed in a certain way, we can develop our interpretation of it through explicitly building upon possibilities opened by how it was disclosed and pre-understood.

While Heidegger is focused on describing the experiential phenomena of pre-understanding, it is easy to see that there are social mechanisms at work there. For instance, pop music prejudices are systematically manufactured by a powerful culture industry, which produces, promotes, hypes and sells musical concerts and recordings (Adorno & Horkheimer, 1947/1972). More subtly, composers adopt mechanisms that contribute to pre-understanding. The system of Western classical tonality, which most music composers employ, is one example. Although music theory defines 12

[3] Citations of German publications list publication / translation year, with German / English pagination.

tones to the octave, virtually every classical musical piece focuses on a subset of those 12 tones. For instance, a piece in the C Major scale primarily uses the 7 notes of the octave that are white keys on a piano. Different scales produce different pre-understandings of mood for listeners.

The alternative twelve-tone approach of serial composers like Schoenberg was an attempt to avoid the pre-understanding fostered by tonal composition. Schoenberg arranged all 12 tones of the octave in a series, and his serial pieces ran through their series before repeating any tone (Adorno, 1948/1973). That eliminated the suggestion of an emphasized key and removed corresponding prejudices about the piece for the audience. The audience then had to overcome the consequent feeling of disorientation and search for other interpretive features of the music. Although he sometimes rejected the tonality of traditional keys, Schoenberg retained the timbres of orchestral instruments and the emotionality of standard patterns of loudness (amplitude) and speed (tempo).

The pioneers of e-music extended Schoenberg's rejection of classical tonality to other parameters of sound in their compositions. Webern—still within the Schoenberg school—integrated loudness into the serialization process, emphasizing silence at one end of that parameter's scale. Silence was transformed from just an implicit rest to slow down notes, into an explicit (disclosed, hearable) composed element. Silence functioned as "negative space" between consecutive sounds.

The vision of e-music was influenced by Edgar Varese and others who foresaw the possibility of composing with arbitrary timbres, not just the characteristic sounds of traditional physical instruments. The new science of acoustics and the developing technologies of electronic sound production suggested creating sounds with any desired characteristics. In theory, the sound of a note played on a piano, organ, guitar or violin—while quite complex—could be scientifically analyzed in terms of its pitch (frequency), timbre (overtones or waveform), and the attack, sustaining and decay of its loudness (amplitude envelope). Sounds could be produced and manipulated by electronic devices (oscillators, controllers, filters, modulators, etc.), creating radically new sonic material through the total organization of the sound parameters (Eimert, 1957). Subsequently, it was possible to define a sound digitally by specifying with a computer its amplitude at each of thousands of microseconds. These individually constructed sounds could then be combined into a sound composition by splicing tape recordings of fabricated and/or "found" (recorded) sounds, playing them sequentially on a synthesizer (Figure 1) or aggregating them with a sequencer.

Figure 1. A 1975 Moog synthesizer. Photo from (Wikipedia_contributors, 2021).

E-music eliminated many of the familiar aural clues that provided a pre-understanding to an audience. Historical developments in musical composition met resistance from changes in the audience of music. The reproduction of music through radio and records had created a huge audience for music. However, much of that audience did not have the cultural background to interpret and appreciate classical music, such as Schoenberg's serial music. To people who were not oriented to exploring the new potentials of sound production, works of e-music could sound like "just noise"—incomprehensible sounds (Neill, 2002). However, as discussed below, e-music opened up a world in which the nature of noise was itself disclosed as interpretable through a technological understanding of its being.

(b) The Working of the Work of Art

In an essay central to his middle period, Heidegger focused on the being of art. *The Origin of the Work of Art* (1935/1963; 1935/1964) proposes that an art work can disclose a world in which people may encounter the being of tools. For instance, van Gogh's painting of a peasant woman's shoes (Figure 2) discloses the being of her shoes as embedded in the peasant's world:

> Van Gogh's painting is an opening-up of that which the tool, the pair of farmer's boots, in truth *is*. This being steps out into the unconcealment of

> its being…. There is a happening of truth at work in the work, if an opening-up of the being happens here in that which is and how it is. (Heidegger, 1935/1963, S. 25, my translation)

Figure 2. Van Gogh's painting *A Pair of Shoes*. Van Gogh Museum, Amsterdam. Photo by author.

Heidegger proposes that the oil painting of the shoes discloses the nature of the shoes as serviceable and reliable tools in the peasant's world. This represents a reversal of perspective from *Being and Time*, in which the being-there (*Da-Sein*) of the viewer discloses the painting within its relations in the viewer's and peasant's networks of tools and concerns. Here, being is disclosed by artworks as well as by human Dasein.

In *Being and Time*, "Dasein" is generally assumed to correspond to an individual's human existence. However, Dasein's openness is not necessarily a matter of cognition by an individual mind. Consider, for instance, an audience at a concert: Their group listening opens the music's world, as jointly understood by the collectivity. Then, the term "Dasein" refers to the shared being-there of the group at the musical event, an instance of being-there-with-others or group cognition (Stahl, 2006). So, the Dasein of *Being and Time* can involve the disclosure of a world to an individual person, a group working together, an audience of some event, a culture and/or even generic inauthentic common-sense understanding.

In Heidegger's consideration of art, the opening of being can take place through a work, such as a painting, jug, sculpture or poem. Such works disclose meaningful worlds. A tension (struggle) exists in these works between disclosing (world) and concealing (earth). For instance, by opening access to the world of the shoes, van

Gogh's painting conceals its own earthy materiality as paint on canvas. Heidegger refers to this tension as a *Riss*, which in German means tearing apart, but also the design, outline or boundary. This boundary is particularly apparent in sculpture. A wood carving, for example, opens the space around and between the surfaces of the wooden forms that make up the sculpture's design, while the wood itself—with its internal structure, physical strength and materiality—lies hidden below the surface. As a bodily object, a sculpture reveals one side at a time, concealing visual access to temporarily hidden planes, which are implicitly indicated as around the bend.

Heidegger argues that van Gogh's painting discloses the nature of the shoes. However, this analysis only works because the painting is representational. Heidegger misses the painting's deeper art-historical importance: the relationship to impressionist revelations about light and shadow, or van Gogh's own exploration of brushstroke as an element of the materiality of paint. The significance of van Gogh's paintings does not primarily have to do with how they disclose the lives of the people or the being of the tools represented in the worlds of the paintings. More important are his techniques of applying paint to the canvas, leading to the emergence of abstract art as exploration of the materials, geometry, light and texture of oil painting. By focusing on the painting's representational function, Heidegger misses much of its historical import.

The year after Heidegger's essay on art was written, the Marxist literary critic Walter Benjamin published *The Work of Art in the Age of Mechanical Reproduction* (1936/1969). This essay can be read as a (possibly intentional) response to Heidegger, who does not acknowledge the historic changes in art. Benjamin reflects on the essential transformation from painting to mechanically reproducible forms of imaging, such as lithography, professional photography, silent film and sound movies. One can easily extend this technological development forward with box cameras, Polaroid, Photoshop, iPhone selfies, Instagram, YouTube and TikTok.

Benjamin delves into what takes place in historic transitions due to reproducibility, such as the transformation from live theater to film. In a play on stage, the actors take on the roles of human characters and present them in a unique setting. By contrast, in the production of a movie, the actors are treated more like props, who adopt isolated poses, which are later edited together by a complex process involving many professionals and technical processes. The produced movie—having lost the "aura" of the unique occurrence—may then be seen by viewers anywhere and at any time. What once took the careful coordination of people (cast, audience, theater staff) coming together in space and time, can now be effortlessly reproduced anywhere. What formerly opened an innovative world is now constrained as a commodity for mass consumption.

Theodor Adorno, music critic and friend of Benjamin, extends the analysis to music and the "culture industry" (Adorno & Horkheimer, 1947/1972). He argues that commercial pop music and big-band jazz represent trends in music resulting from its popularization through mechanical reproduction in recordings, similar to that of film (Dunn, 1992). In earlier periods, people learned to play musical instruments and accordingly better understood what was involved in producing music, but records spread music to people with little understanding of music theory. Adorno discusses the dialectic of enlightenment, in which social progress toward increasing knowledge and morality has always been accompanied by regress. Benjamin's examples of mechanical reproduction of art works illustrate this: the increasing democratization, popularization and accessibility of art due to technological progress in means of production has been accompanied throughout history by regression in the innovation of popular works and the depth of understanding by the audience. While Adorno's dialectic of culture parallels Heidegger's abstract notion of the *Riss* as a conflict in art's impact, Adorno and his critical-social-theory colleagues such as Benjamin, Horkheimer, Marcuse and Habermas delve into the social and historical processes through which this tension occurs. The history of e-music illustrates the decline in the public's musical understanding in the following sections, as the ontological vision of e-music is gradually lost in the commercialism of pop music using electronic technologies.

(c) Art in the Age of Technology

In a late essay, Heidegger returned to the project of *Being and Time* with a discussion of *Time and Being* (1962/1972). Here, he maintains that the disclosure of being is given by successive "epochs of being" throughout history. For instance, things were disclosed as creations of God during medieval times and now they are given as material for, or products of, technological manipulation. This is Heidegger's approach to integrating history into his ontology. The question is whether this is an adequate comprehension of the role of history, particularly in the working of artworks.

According to Heidegger, works of art set truth into work as the disclosure of being, where being is always disclosed in accordance with the prevailing epoch of being. Consider how this applies to music. Works of music open worlds—acoustic landscapes of meaningful sound. When the music is self-consciously technological, such as Stockhausen's *Kontakte* (1962), the sonic world is opened and understood as a technological product, and the technical parameters may be made perceptible (heard as such). The nature of the sound is itself disclosed, rather than appearing as a presence of some other being (instrument, performer).

E-music provides a propitious example of technological being. E-music treats sound from a technological perspective (Figure 3): as technically defined in objective, measurable terms of frequency and amplitude and as material for production and manipulation by technological means (Manning, 2004; Puckette, 2007). Even individual notes can be composed out of sound parameters—generating new kinds of sounds. Works of e-music often evoke reflections on our technological age, such as images of space travel or video games. At the same time, they are frequently heard as noise—either the din of mechanical and technical contrivances or the incomprehensibility of strange sounds.

Figure 3. Karlheinz Stockhausen in the Electronic Music Studio of WDR, Cologne, in 1991. Photo by Kathinka Pasveer, retrieved from https://commons.wikimedia.org/w/index.php?curid=8385683.

Within a Heideggerian viewpoint, noise is sound that is not pre-understood: It makes no sense to the listener; it is not disclosed as meaningful (Stahl, 1976). The pioneers of e-music had to explain to the listening public what they were trying to do with sounds that seemed to *be* just noise. Verbal descriptions of the aims and methods of e-music works supported understanding, helping the music to be disclosed in a way that would not be rejected as incomprehensible noise but could be interpreted within a context (world) of aural being (explorations of sound). Rigorous theoretical considerations by e-music composers abounded in the 1960s: Stockhausen's *Texte*, Xenakis' *Formalized Music*, Boulez' *Boulez on Music Today*, and articles in *Die Reihe* and *Perspectives of New Music*. In this way, the composers acted as ontologists, elucidating the hermeneutics of e-music. For Heidegger, ontology is simply the explication or radical interpretation of everyday understanding, which was particularly urgent for e-music, given the extent to which it rejected many of the traditional crutches of music appreciation.

The working of an e-music composition discloses something of the ontology of sound. In being crafted by a composer, performed by a musician, appreciated by a listener and analyzed by a critic, the work makes something of its sonic ontology visible to each of these audiences. They each articulate a different narrative of their interpretations, based on their concerns, expectations and pre-judgments. However, a successful work must connect these communities within the shared world opened by the e-music work.

Even *noise*—which is generally taken to be a rejection of understandability—can be interpreted through a technological approach to sound and its theory. E-music analyzed and worked with noise. In technical terms, "white" noise is a mixture of all frequencies of sound. It can, for instance, be digitally generated with a random-number generator specifying all frequencies stochastically. White noise can then be manipulated with filters and amplitude envelops to produce musically interesting noise sounds within selected pitch ranges. Controlled noise can be integrated into music to add depth, as rock musicians did with feedback from speakers and electronic distortion of their instruments, but now manipulated across the spectra of its technical parameters. As discussed below, the history of e-music provides a rich example of how the technological analysis of musical sound was applied to compositional control over sound, including noise. It illustrates how a work of music opens a world in which the historical being of sound is disclosed… and transformed.

The way in which a new understanding of noise arises through the composition of e-music suggests that Heidegger's analyses inadequately appreciate the role of the artist's productive labor that makes the work of art what it is. The artist does not merely bring forth a work whose being is given by history, but rather structures the details of the work's being through the artist's creative labor (working). This may point to a general problem with Heidegger's ontology. While providing a brilliant phenomenological description of how beings are disclosed, he does not describe how an individual being (whether thing, tool, work or Dasein) comes to be disclosed not only as the kind of being it is, but also as the unique being that it is. Even if one focuses on the artwork's being, it is necessary to analyze how that being becomes specified.

What is the relation of an artwork's working to the artist's historically situated work? Perhaps what Heidegger discusses as the *Riss* between earth and world in the being of van Gogh's painting was set into the artwork by van Gogh's artistic working with earth and world in creating the painting, as they interacted within the play of van Gogh's historical world. How is his painting's earth related to the artist's brushstroke style and how is the painting's world related to the life of contemporary farmers? How is the working of noise in e-music structured by the composer's work in creating the music?

In his essay on *The Thing*, Heidegger (1950/1967) considers the example of a jug to discuss in general how things are disclosed. He suggests that the being of the jug is centered on its interior void, which can be filled with water or wine and can offer it for pouring and imbibing. Heidegger seems to have in mind a hand-crafted ancient Greek jug, which functioned with the "aura" of a unique thing in the here and now—not an interchangeable jug from a factory assembly line in the technological era. However, he does not describe how an individual jug concretely comes to be what it is—with its unique character and aura as well as with its particular functional shape—through the potter's effort, rather than a factory's production.

Learning to make traditional pottery involves acquiring skills and knowledge to be able to produce jugs that can fulfill a well-functioning jug's tasks. Creating an aesthetically pleasing jug involves a series of many phases: acquiring and preparing the clay; gathering the tools and equipment; centering the lump of clay on the rotating potter's wheel; opening a void in the lump; pulling the sides up in several pulls without the sides collapsing; shaping the interior curve to match the exterior curve; partially drying the piece to give it strength; trimming the thrown piece and cutting a foot on it; gently shaping a spout that will pour without dripping; attaching a pulled length of clay for a handle that will fit a human grip and provide balanced lifting; slowly drying the clay without cracking; optionally etching design in the surface; firing the jug; glazing it and firing it again.

Each stage of producing the jug by hand is an exploratory experiment and the final product is always somewhat of a surprise. There is an interplay between one's aims and the results. At each successive stage, one is confronted by an object with its own character. The back and forth between the artist's strivings and the evolving work's response is typical of all forms of artistic production. An artist does not simply impose a pre-conceived template on some physical material (clay, wood, pigment, sound, etc.). There is an interplay between creator and created, between mind and eye (Merleau-Ponty, 1961/1964), between disclosing and concealing, between enlightenment and regress. This interplay during creation is then established in the work of art as its specific working or unique being.

In *The Origin of the Work of Art*, Heidegger writes about the connection of the work to its creator:

> Although the work of art becomes actual only in the carrying out of the creating, and thus depends upon this act for its reality, the nature of creating is thereby dependent upon the nature of the work…. From the perspective of the achieved outlining of the nature of the artwork—according to which, in the work the happening of truth is at work—we can characterize creating as a letting something emerge as something brought forth. The work's becoming a work is a way in which truth becomes and happens. (Heidegger, 1935/1963, S. 48f/p. 683f, my translation)

Here, Heidegger acknowledges the craft of the artist but subordinates it to the working of the work itself that opens a world and reveals something. Heidegger's shift from the artist to the work as primary creative agent is central to his philosophic contribution, overcoming the subjectivism of previous philosophy and aesthetic theory. However, his presentations lack adequate concreteness and tend to leave underlying processes vague and mysterious. He does not recognize the ontological role of the artist in shaping how the individual work that is brought forth becomes what it is as a particular work with a unique way of working. While it is true that the potter's work is guided by the nature of jugs, each jug is different in detail due to the specifics of the potter's work.

The creation of art is always a historically mediated process, reaching back to the stone age for pottery, painting, music, sculpture and poetry—while innovating into the future. The artist pushes previous inquiries further, confronting issues that arose in past works and adopting techniques that have been developed by earlier artists. For instance, the potter, in creating a jug that will open a world that discloses people enjoying the fruits of the earth and skies, explores how best to accomplish that, given the historically prevailing conditions and technologies. The potter selects the right clay and glazes. She experiments with how different construction techniques, various spouts and specific handle curves contribute to how the unique created jug works to open a specific world, in which the jug can work effectively as desired. The potter's craft, worked out on a specific, concrete piece of work, refines the being of that work, deciding how it will work, that is, how it will be.

Only through the historically situated labor of the artist is the work of art established the way that it is (its being) in the world that it opens—not just through historical change writ large, but through the concrete application of specific production technologies under particular socio-economic conditions. This process is suggested by Heidegger, but not investigated in sufficient social and historical detail. Benjamin's studies of mechanical reproduction and Adorno's writings on the culture industry provide important extensions and correctives to Heidegger, showing that in addition to the artistic and craft-related explorations of the artist, the current forces of production (e.g., mechanical reproduction) and the prevailing social/economic relations (e.g., commodification by the culture industry) affect the way a work opens (and conceals) its world.

The development of e-music illustrates the complexity of historic processes of progress and regress. We have already seen how the composers of e-music explored innovative ways to open acoustic worlds. However, there is also a retrograde movement: Technology enables new sounds but removes compositions of these sounds further from the comprehension of an audience. The origins of music in the human body (heartbeat, breathing), dance and the physicality of playing physical instruments are replaced in e-music by technical tasks that manipulate abstract parameters on machines. For instance, Stockhausen often computes the timing and other parameters of sounds mathematically rather than through bodily movements (Neill, 2002). Live, responsive performance is supplanted by methodical efforts in electronic laboratories far removed from potential audiences (Figure 3).

The issues of performance and audience raised by e-music had to be addressed. They led to the incorporation of sounds and techniques pioneered by e-music being integrated into and co-opted by more popular musical forms. This brought in live performance, reintroducing and even accentuating movement of the human body as a basis of repetitive rhythm (Glover, 2013). The electronic synthesizer, the sequencer of recorded sounds and even the computer-generated tape became additional musical instruments, eventually often subordinated to traditional instruments (piano, guitar) and practices (tonality, common tempo) (Neill, 2002). Innovative e-music sounds or rhythms were often used to introduce pieces of pop music that soon devolved into traditional song styles (Dunn, 1992). New genres also appeared, incorporating and concealing e-music techniques: electro-acoustics combining synthesizers, tape and instruments; rap mixing drum machines and recorded sounds; trance-music exploiting ethereal resonances and mechanized repetition. These hybrids were easier to market as cultural commodities and they frequently lost their aura of innovative openings to worlds of sound as disclosed in e-music. Electronic music had a profound impact on the history of music. It fueled a diverse array of new genres, enabling innovative ways for music to be and work. Simultaneously, the technologies of electronic music were coopted by the pop-music culture industry, slightly modifying commercial music, but ignoring the e-music vision of opening worlds that disclosed the nature of sound. This history of e-music is much richer than suggested in Heidegger's simplified history of being.

(d) Relations of Artistic Form

One of Heidegger's last publications, *Art and Space* (1969/1973), is associated with his contact with sculptors (Mitchell, 2010). Here, Heidegger rejects the traditional view of sculpture as formed matter within an objective, pre-existing extended space. Although he does not discuss any specific example of sculpture, he considers how sculptures define "places" in relation to each other. Heidegger resorts to his critique in *Being and Time* of Newtonian space in favor of human places, now expressed in his later terminology. He writes that sculpture does not passively occupy homogeneous three-dimensional space, but opens-up regions in which people can meaningfully live:

> Sculpture [is] the embodiment of places. Places, in preserving and opening a region, hold something free gathered around them which grants the tarrying of things under consideration and a dwelling for man in the midst of things. (Heidegger, 1969/1973, S. 11/p. 7)

Sculpture, as a form of artwork, can reveal spatial being. Henry Moore's *Three-Piece Sculpture* (Figure 4) illustrates a region of places opened-up and embodied by a sculpture. The massive bronze forms of bonelike knobs and points of Moore's sculpture define multiple *places* in relationship to each other. They reflect each other as related, but each unique. The interconnected forms press upon one another and support each other, creating a complex of places that defines a structured region.

Figure 4. Henry Moore, *Three-Piece Sculpture: Vertebrae*, 1968-69, bronze, approx. 3' x 8' x 4'. Hirschhorn Sculpture Garden, Washington, DC. Photo by author.

By integrating three cast pieces into a single sculpture, Moore's work opens negative spaces between the pieces, in addition to and uniting the open areas surrounding the embodied forms of the individual pieces. Here, the accessible space is not an unstructured abstract volume, but a well-defined system of openings that invite the beholder's eyes and body to circulate through and around the work to explore its variety and interrelationships. The work of sculpture works to disclose a structured space that would not exist without it, in which people can tarry and experience a world of meaningful inter-related places within a larger region.

The working involves a dynamic between revealing and concealing. As a work, a sculpture opens a devoted area around itself, structured by the sculpture's massed forms, which extends out from that work. The surfaces of the forms are revealed, but they simultaneously conceal what lies below, behind or beyond the surface: the interior of the wood, stone, bronze or other material, as well as the voids, hidden surfaces and surroundings.

Certain sculptures may attempt to open-up the concealed interior—for instance by poking a hole into or through the surface's forms or by chipping away the smooth outer surface to expose internal material. Or they may reveal the effort of carving the material by leaving traces of that human effort and procedure. Through such elements of the work's design, the interior is opened-up, but then simultaneously closed along the new surfaces (outline or *Riss*).

Negative form can be viewed as an effort to reverse what is concealed and what is revealed. In some sculptures, the space is revealed by simply outlining it or otherwise indicating it. In others, the normally concealed interior space is opened-up by providing just a structure to define it as a space. For instance, one could consider Giacometti's thin plaster sculptures of women to be presenting just the interior core of a human figure, absent the usual concealing layer of the body's flesh and skin.

Sculptors like Moore and Giacometti explore materials, sizes, shapes, representations and topologies that allow their sculptures to work to open worlds, places and regions for human tarrying. Through their sculpting, they pursue ontological investigations of how to let works be, such that they open certain sorts of worlds. For instance, Moore's sculpture of vertebrae incorporates his lifetime of sculptural studies of boney forms, reclining human figures and multi-piece interactions. Giacometti spent decades of his career building up and chipping away thousands of plaster representations of female models, struggling to get the sculptures to disclose the being of the human body in a specific way. Their skilled working with their materials, experiences, technologies and techniques defined their tireless working to create works of art. The works did not suddenly appear but emerged under their meticulous and relentless efforts to produce works with specific kinds of being. In fact, for leading modern sculptors like Rodin, Brancusi, Giacometti, Degas, Barlach and Moore, the finished sculptures are less important than the work of sculpting, the endlessly repeated working of their forms, materials and techniques to bring forth pieces that set into work some truth that they are implicitly struggling toward and gradually approaching.

Analogously to sculpture, e-music can be heard as sequences of sculpted moments of sound, often delimited and individuated by silences. In a lecture on "*The Four Criteria of Electronic Music*," Stockhausen specified that e-music was characterized by its focus on composing relations among times, tones, spaces and noise. His defining features of e-music were:

1. Unified time structuring.
2. Splitting of the sound.
3. Multilayered spatial composition.
4. Continuum of tone and noise. (Stockhausen, 1972)

His composition *Kontakte* was structured by de-composing sound into its parameters of temporal duration, timbral components, spatial location and noise band, as well as pitch and loudness—each defined along scales. Here, Stockhausen extended the intervallic serialization he learned from Schoenberg and Webern to all the parameters of sound, creating tones that had not been composed before, in more complex relationships, opening new possibilities of acoustic places and moments layered upon each other to create temporal structures.

Music, more explicitly than other art forms, creates sequential temporal forms. The being of a musical work according to Heidegger's analysis of art is its working, which is a process that necessarily unfolds in time. The character, being or origin of a work of music is not an attribute of its immediate presence but is disclosed through its manner of opening a sonic world temporally. Specifically, e-music harnessed electronic and digital technologies to control the timing of individual sounds, of phrases and of overall compositions. E-music explored innovative timings of sound wave forms, envelopes, sequences and movements. It not only replaced traditional timings but developed a wholly new systematic approach to temporality as a central dimension of control and composition. Some of Stockhausen's compositions allow for the sequencing of movements or even of sounds to be determined by chance, rather than by the score, making explicit the role of temporal sequence in the being of the sonic work.

Stockhausen methodically explored the being of sound and how works of music open acoustic worlds. He shifted the science of acoustics into a philosophy and ontology of sound by investigating the effects of the various parameters of sound on the working of e-music compositions to achieve musical works with innovative being. Many of Stockhausen's major pieces of e-music were designed, defined, composed and refined by him to disclose selected aspects of the being of sound through the working of the musical work. For example, his composition, "*Beethoven Opus 1970*," electronically transformed moments from Beethoven's oeuvre to re-disclose the acoustic being of Beethoven's sounds in the technological era. His monumental "*Hymnen*" manipulated sound samples from national anthems to disclose how they opened nationalist worlds, just as Hendrix's distorted electric guitar version of "*Star Spangled Banner*" opened a politically construed world for his audience at Woodstock during the Vietnam War.

As part of its working, a work of art functions as a communication between its creator and its recipients. It discloses to the listener/viewer/preserver what is rendered perceptible in the work—an opening of worlds that can be shared. Heidegger notes about the audience role:

> Preserving the work does not individualize people to their life-experiences, but draws them into their belonging to the truth that happens in the work, and thereby grounds their being-for and being-with-one-another as the historical standing-out of being-there (Da-Sein) in relation to unconcealedness. (Heidegger, 1935/1963, S. 55f/p. 690, my translation)

Thus, the work functions to build historically situated inter-subjectivity, grounded in the work. It opens ontological understanding: a shared understanding of the being of the sounds, work and world.

An artwork brings a work into the world, opening a space for it to do its work in its historical social setting. Of course, a work of music, painting, pottery or sculpture does not appear *sui generis*, on its own, as Heidegger's presentation might lead one to believe. Just as the clay jug, van Gogh's painting or Moore's sculpture required a complex crafting, based on culturally developed and passed-down practices, Stockhausen's compositions called upon the skill and intellectual effort of a world-class artist and drew upon the state-of-the-art technical world to compose works with the proper being.

While Heidegger's focus on the being of the work is central to his contribution, it is also necessary to consider the role of the artist and the audience in not just passively dwelling in the world opened by the work, but also in actively determining the concrete and specific way a work, as a unique being, works. Talented artists are ontologists, sculpting the being of their works, as evidenced by the historically innovative forms of disclosure of the worlds they open.

e-Music in Socio-historical Context

Heidegger's writings on works of art can provide ground-breaking ways of viewing art, including music. They provide an alternative, ontological perspective from that offered by previous, subjectivistic or positivistic Western thinking about art, space, time and being. However, when compared with discussions by writers like Adorno and Benjamin, approaching from an analysis of historical development based on Marx, one finds Heidegger's descriptions lacking sufficient depth of social and historical considerations. Heidegger's writings take on a feeling of somewhat superficial jargon or mysticism (Adorno, 1964/1973). How does disclosure of a unique creative work take place concretely? How are the historical epochs of being given, such that one flows into the next?

The social theorist Giddens proposed a notion of "structuration," whereby social institutions and forces do not so much influence the behavior of individuals in a given society, as they are themselves produced and reproduced by the habitual practices of those people and their communities (Giddens, 1984). In this view, social structures exist only in and through these enduring and evolving reproductive patterns of repetitive behavior: Their being is temporal. The history of e-music—as a developing body of compositional techniques—can provide a model of the concrete social and historical kinds of processes of structuration by which the history of art and the development of the technological character of our age intertwine dialectically. In particular, we can see the historical dimension of e-music involving the situated being and activity of the works, composers and audiences as they interact in socio-historically concrete circumstances to structure the being of the e-music pieces.

The fact that e-music compositions reflected the availability of evolving technological means was not the result of some mysterious arrival and imposition of a new "epoch of being." Rather, the production and working of this music itself anticipated, proclaimed and contributed to the historical age. In the development of e-music, composers did not just take advantage of newly existing technologies to create innovative sounds. They also anticipated potential novel techniques and often invented the requisite tools. The working of the works of e-music propelled this historical change as well as disclosing it to the ears of the audience.

The history of being consists of the repetitive behaviors of people, such as the cultural practices embodied in the working of art works; it is not an outside force or source of determination, but an "eventing" (*Ereignis*) of the working of the historic works. E-music helped to define the technological era by incorporating technological elements into the succession of sonic works, which both reproduced established approaches to musical composition and on their basis produced novel extensions to it, which could in turn then be taken up in future works in unanticipated ways. E-music composers and their works literally made history—the history of technological being. As Marx famously put it, "People make their own history, but they make it under inherited, found and pregiven conditions not chosen by them" (Marx, 1852/1963, p. 15).

Social practices are collected, preserved and expanded within the contemporary culture, as a massive collection of mostly tacit patterns of behaviors, which provide the conditions for the creation of new works of art. Socio-cultural practices are analogous to people's behavioral habits; Bourdieu (1972/1995) showed how much of one's "habitus" is grounded in one's body and personal artifacts (e.g., clothing, food, home and kinship structure). Technological practices of music production are embodied in the body of work of e-music compositions, as written, performed, recorded and heard.

The habitus, culture, institutional base of structuration or knowledge of compositional technique is a "system of durable, transposable dispositions" (Bourdieu, 1972/1995, p. 72). Skill or expertise does not consist of a store of propositional statements, mental representations or explicit rules, but as the ability to engage over time in various extended practices. It is a matter of dispositions or the likely ability to respond extemporaneously to similar situations—to "go on" as Wittgenstein (1953) said—rather than fixed propositional knowledge or trained behaviors. It grows and becomes better defined through reiteration. The work of a composer or the working of a composition takes place by improvisational reproduction of the repetitive practices that occur in this system of habits. The replication typically takes place tacitly, without following an explicit rule of behavior or aiming at a preceding intention—adapting previous models intuitively and creatively, neither mechanically nor consciously. It may be accompanied—especially retrospectively in reflection—by a folk-theory narrative or account. However, the way to comprehend it theoretically is to understand it historically in terms of the forces and processes that mediated the original occurrence of the practice, rather than only the circumstances surrounding its current repetition.

E-music evolved out of previous compositional practice, such as established approaches to serialization and orchestration. The addition of new sonic forms and techniques involved reflective and articulated considerations by composers concerning their aesthetic circumstances and possibilities. These additions contributed to the history and growing scope of e-music—often being incorporated in updated technologies, such as synthesizers, which helped to institutionalize the practices made easier and standardized by such tools. Technological artifacts (tools, works, texts) could then serve as "immutable mobiles" (Latour, 1990) to spread the innovations or "boundary objects" (Star, 1989) to bridge different compositional approaches. There was an e-music community of composers, performers, critics and audiences, within which processes of apprenticeship and "legitimate peripheral participation" (Lave & Wenger, 1991) transformed the community as well as the nature of new works. As time went on and the once shockingly innovative practices of structuring sound became habituated to by audiences as well as composers, they tended to lose their impact and become integrated into the commercial music industry. Thus, history happened. That history can best be understood by interpreting the e-music worlds in which the new practices originally occurred.

Viewed from a critical socio-historical or Marxist perspective, Heidegger's analyses are not sufficiently grounded in social reality, habitus and structuration processes. As already noted, Heidegger over-looked the post-impressionist historical context of van Gogh's painting. When van Gogh painted the peasant's shoes in 1886, photography had already become well established as an art form and was about to become readily available to the public with the Kodak box camera, so there was little need for painting to imitate visual reality. Rather, van Gogh's contemporaries were exploring effects of lighting and techniques of applying pigment. Van Gogh's contribution was to take up the lessons and experiments of his predecessors and colleagues and to create works that opened new possibilities in the technology of painting. The evocative quality of his painting of shoes—that captured Heidegger's attention—was due precisely to its shift away from photographic realism to a focus on the painter's uses of light and pigment, which dramatically highlight the emotional, social and situated character of the subject—missing from standard photographic images.

Heidegger similarly ignores the meticulous efforts that go into making a pottery piece, including techniques and technologies developed socially over generations. Likewise, sculpture opens space through the complex processes that go into forming the sculpture, through which the sculptor fine tunes the being of the work and of the world it opens. Perhaps the artist's ontological contribution is even clearer in e-music. This artistic movement explored how to create works of music that effectively opened worlds of sound. It thereby showed in technical detail how the being of individual sounds could be constructed and then composed into specific works of music that would disclose particular new worlds.

It is also important to recognize that the historical process of e-music ultimately unfolded concretely and dialectically within the relations of commercial music. For music in general, the mechanical reproduction (tapes and records) and later the digital production of sound (mp3s and iPods) not only provided for a tremendously expanded global audience for Western music, but also transformed the nature of musical reception, as anticipated and documented by Benjamin and Adorno. By increasing control over the timing of sound events and even automating their repetition, e-music led not only to synthesizers of universal sound production, but also to sequencers of rhythms, such as popular drum machines.

The long-term result of the e-music genre was not just to open the world of sound as understood in technical terms of frequency, amplitude, noise, algorithmic patterns, and relations among temporal moments or acoustic places. Also, it was to devolve into commercialized forms of disco, rap and new-age trance music, which could be profitably manufactured with drum machines (Dunn, 1992). Much of what e-music had revealed was thereby re-concealed by pop music, as practices of music production became more distant from the original e-music innovations and more enmeshed with business practices. The relations of production in capitalist economies (commodification and monetary profit) channel the evolution of the technological means of production (Marx, 1867/1977). This must be recognized in order to extend the understanding of music, art and being from the perspective of Heidegger's ontology.

In addition to painting, pottery and sculpture, Heidegger considered poetry. For him, this was the most important form of artwork, because it involves the working of language. Language is the house of being, in which social practices are articulated and preserved, as they define the flow of the history of being. Unfortunately, it is beyond the scope of this essay to consider the working of poetry and the role of language, as would be necessary for a more complete reflection on Heidegger and art.

Heidegger's philosophy of being, as it evolved through his life's work, provides useful ways of considering the nature of music and other art forms. Conversely, considerations of socio-historical aspects of artistic production provide important correctives to Heidegger's incomplete analyses. E-music offers an example of musical development—contemporaneous with Heidegger's writings—that opens a view that can both confirm and extend his insights.

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Bio

Gerry Stahl followed the development of e-music while researching a philosophy dissertation on Heidegger and Marx in Germany and the USA in the 1960s and 1970s—and even experimented a bit in electronic and computer music, without success. His eventual career was in information science and research on computer support for group cognition (see http://GerryStahl.net). He retired as emeritus professor from Drexel University and now carves wood sculpture in Cape Cod.

6. Introducing Theoretical Investigations

By compiling his aphoristic *Philosophical Investigations*, Wittgenstein (1953) provided a provocative image of how philosophy could apprehend the world—in particular how it should understand language about the world. In founding and editing the *International Journal of Computer-Supported Collaborative Learning* (*ijCSCL*)—as a collective effort with many leading researchers from around the world—I intended to craft a venue for CSCL researchers to publish theoretical reflections on their work and on the nature of computer-supported collaborative learning. In addition, in my own CSCL research, I always tried to derive theoretical insights from the analysis of recorded student discourse. Just as Wittgenstein believed that a certain form of conceptual analysis was needed in philosophy, I was convinced in the relevance of certain kinds of theoretical reflection to the burgeoning field of CSCL.

In the spirit of Wittgenstein's collection of deliberations, I now assemble highlights of the journal and of my writings that I believe can contribute to an understanding of concepts and themes central to the field of computer-supported collaborative learning. Wittgenstein's presentation was self-consciously non-systematic. His paragraphs (like Einstein's transformative papers in physics) primarily pose thought experiments, which tend to problematize established ways of thinking that have become second nature. Similarly, I do not intend to lay out a clear roadway for educational transformation or a logical edifice of theory. Rather, I hope to question outmoded assumptions and stimulate creative exploration in CSCL theory, methodology and practice. However, in distinction from the thought experiments of Wittgenstein's philosophy, the *ijCSCL* papers and my own research reports are thoroughly grounded in analysis of empirical interaction data.

Looking over the collection of papers collected for this volume of *Theoretical Investigations*, I perceived an emergent vision of CSCL, quite distinct from traditional educational research. I have therefore written two new introductory essays to provide an overview that suggests this vision and that connects it to theoretical concepts. The Introduction and these two essays constitute Part I of this volume.

The first of these essays [Investigation 1] argues for a particular vision of CSCL, centered on a specific paradigm of collaborative learning, which is expanded by the sequence of *ijCSCL* papers [Investigations 3-17] that constitute Part II of this volume.

The second essay [Investigation 2] reviews contributions to a theory of group cognition as foundational for CSCL research and practice. The papers covered by this essay [Investigations 18-28] are gathered from reports of the Virtual Math Teams (VMT) research project. These papers constitute Part III of this volume.

The impetus driving the research field of CSCL has been evolving over several decades (Stahl, Koschmann & Suthers, 2006). However, the multifaceted knowledge required to implement CSCL pedagogy widely in schools was not available until now. Appearances to the contrary, elements of such knowledge now largely exist—albeit in a preliminary, fractured, distributed and uncoordinated manner. For instance, much of the needed knowledge is described, pointed to or illustrated in past volumes of *ijCSCL*. Unfortunately, however, some of the most innovative or penetrating analyses published there have not been further pursued or integrated with each other and with the accepted wisdom of the CSCL field. The present compendium of selected papers from *ijCSCL* is an attempt to document this claim that the necessary components are available and to indicate a possible path forward to realizing a CSCL vision.

The view that students should be active learning agents is as old as our culture, enunciated by Socrates and Buddha, for instance. Over a century ago, Dewey argued for a progressive inquiry approach in modern public schools—although, despite widespread recognition, his approach had limited impact on schooling. Still today, many people conduct research or introduce classroom interventions that they call CSCL, but that lack the elements that we have discovered to be central to effective collaborative learning. It is not sufficient to place groups of students together with arbitrary computer communication technology; one must design, identify and support the defining processes and practices, such as intersubjective meaning making and mediated knowledge building.

The publications selected for this volume from *ijCSCL* build upon historical sources and early CSCL investigations. They suggest: how to simultaneously focus CSCL theory and broaden the field's scope; how to analyze the processes of collaborative learning and mediation of group cognition by computer artifacts and supports; and how to develop innovative technological tools and educational infrastructures to facilitate collaborative knowledge building. Accordingly, they transform and potentially integrate elements of CSCL theory, methodology and practice that can contribute to an ambitious effort to realize the CSCL vision on an international scale.

The papers included in this review all emerged out of CSCL labs (some were summaries of dissertations within the labs; others reported on cross-lab projects) around the world. Significant CSCL investigations generally require teams of researchers, pooling different expertise and perspectives on cognitive theory, analytic methodology and educational practice. They often involve consortia of labs. However, the effort to go beyond scattered research efforts and implement the CSCL vision in schools requires an even greater collaboration—one on a global scale. The present volume aims to substantiate this claim through a review of the central points of selected investigations published in *ijCSCL* and reproduced here. The overview in Investigation 1, written for this volume, indicates how a synthesis of these proposals for CSCL theory, methodology and practice could allow us to reach toward implementations of a CSCL vision. The effort required for achieving this CSCL vision would involve a global collaboration, supported by computer technologies and funded by progressive political will.

As founding editor (with Friedrich Hesse and a distinguished Board) of *ijCSCL* from 2006 through 2015, I selected favorite articles for this volume and commented on them from the perspective of influences on my own evolving understanding of CSCL. I include some articles related to the VMT project, which is the CSCL research I know first-hand. Several of the other publications represent the work of leaders in the field of CSCL research. Many of these articles were among the most cited and downloaded publications in *ijCSCL*. I selected those that had a theory focus or were otherwise suggestive for implementing the CSCL vision. There are, of course, many other insightful theoretical papers available in *ijCSCL*; it was not possible to include them all in this volume. I hope this compilation will stimulate readers to return to early *ijCSCL* issues to unearth other gems.

Throughout the history of CSCL, there has been a tension between various paradigms of research, colloquially referred to as quantitative versus qualitative. The thrust of this collection of papers is that the defining characteristic of CSCL methodology should not be the kind of techniques applied in data analysis, but a focus on collaborative interactions. This is what is definitive of learning or knowledge construction in CSCL. In addition, socio-cognitive and socio-cultural approaches have often been contrasted. The vision arrived at in this volume moves beyond viewing individual cognition (thinking) as peripherally affected by its social context to considering human cognition as itself an inter-personal, social or small-group phenomenon, evolving from a biological and cultural function. Today, cognition involves in its essence a tightly entangled complex of external memories, mediating artifacts and networked interactions. So conceptualized, collaborative learning is no longer a niche educational activity subservient to the needs of individual minds, but a foundational mode of being-in-the-world, from which individual cognition is itself a derived narrative.

Various efforts are underway to harness the opportunities of global networking of information to make course materials from advanced educational centers more broadly available around the world. These include massive open online courses (MOOCs) as well as open educational resources (OER), although these initial attempts rarely adopt a pedagogy of collaborative learning. This volume includes reports of tentative, but systematic attempts to deploy CSCL approaches in national school systems. They are suggestive of an international effort that could prove transformative. Within the vision of human cognition as increasingly global, the goal of promoting worldwide collaborative learning seems inevitable, if challenging.

The selection of papers from *ijCSCL* raise issues of CSCL theory, such as the nature of intersubjectivity, joint attention, shared experience, meaning making, artifact usage, reference, temporal sequentiality, discourse structure, multiple levels of description, primary unit of analysis, external memory, group practices, and group cognition. These issues are explored in the VMT research papers. The VMT Project has already been extensively documented in four previously published volumes:

Group Cognition: Computer Support for Building Collaborative Knowledge (Stahl, 2006). This collection of research reports motivates the design of the VMT Project. It begins with several attempts to design support for collaborative learning and cooperative work. Challenges that arose in these efforts showed a need for deeper theoretic foundations, raising questions the preconditions for productive collaboration. The concept of "group cognition" was proposed to shift the focus of learning to the small group as the primary unit of analysis for investigation. It seemed important to begin to collect data systematically documenting student interaction within a paradigmatic CSCL setting. Final chapters report on initial findings from students chatting about mathematics problems.

Studying Virtual Math Teams (Stahl, 2009) documents the Virtual Math Teams Project as it explored technology for supporting student mathematical discourse. Many issues of pedagogy, analysis and theory were considered in relation to the technological features. The VMT system integrated a shared whiteboard with text chat. Sessions were automatically recorded so that student interaction could be replayed and analyzed in detail by researchers.

Translating Euclid: Designing a Human-Centered Mathematics (Stahl, 2013) reflected on the final version of the VMT Project from a dozen perspectives. At this point, a multi-user version of GeoGebra was integrated into the shared whiteboard, to allow teams of students to construct and explore strategically selected geometric figures and gradually learn to think/discuss geometrically and solve problems collaboratively.

Constructing Dynamic Triangles Together: The Development of Mathematical Group Cognition (Stahl, 2016) provides a book-length longitudinal study of how a specific group of three young girls began to learn dynamic geometry together. The detailed analysis shows how the group successively adopted a productive set of group practices for collaboration, geometric construction, problem solving and mathematical discourse.

Part III of the current volume elaborates theoretical issues that were raised in the published books.

The reader is not expected to read this volume through in order. The twenty-eight investigations are structured so that they can be skimmed, read, studied or skipped in any order. Each is self-contained, incorporating its own problematic, argument, literary style and reference section. Nevertheless, connections and references among the investigations abound—both implicitly and explicitly. It is hoped that the different presentations support and enhance each other, gradually building a sense of the depth and power of CSCL theory as well as the field's potential to empower students to tackle the daunting challenges of the future collaboratively.

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7. A Vision of Group Cognition

Abstract. The field of CSCL—as a unity of academic research and educational practice—is characterized in this investigation by a specific vision of collaborative learning, illustrated by a prototypical research effort. A number of recent publications are reviewed to extend the scope of CSCL in response to contemporary theory and current social issues. This leads to advancing theoretical concepts and frameworks for conceptualizing CSCL research and practice, which contrast with traditional educational approaches. Although these ideas were originally proposed in disparate contexts, they provide the conceptual skeleton of a unified theory for CSCL, which would be distinguished from popular theories of individual learning and would integrate technological support with collaborative cognition. These insights concerning theory have methodological implications for analyzing CSCL interventions in terms of group knowledge-building practices mediated by interactionally appropriated artifacts. Revised forms of analysis can help innovators evaluate CSCL trials during iterations of design-based research. Bridging from academic research to educational practice, two examples of efforts to bring the CSCL vision to scale within national school systems are then reviewed. Finally, a global collaboration among CSCL researchers is recommended for effective implementation of the CSCL vision in education worldwide, based on the presented conceptualizations of a unified theory of collaborative learning and their implications for evaluation of CSCL technical and pedagogical designs.

Keywords. CSCL theory, group practice, design-based research, scaling up, cognitive evolution, group cognition, sequential analysis, knowledge objects, referential resources, temporal analysis, instrumental genesis, intersubjective meaning making.

Defining a CSCL vision

Previous attempts to circumscribe the field of CSCL have faltered; the target is so nebulous, controversial, disjointed, multi-dimensional and agonistic. Most have tried to specify operational criteria for inclusion of papers in the CSCL corpus (Akkerman et al., 2007; Jeong & Hmelo-Silver, 2016; Jeong, Hmelo-Silver & Yu, 2014; Kienle & Wessner, 2006; Lonchamp, 2012; Schwarz & Wise, 2017; Tang, Tsai & Lin, 2014).

However, such attempts to apply "objective" standards generally fail to include some of the most important contributions, especially those that are more theoretically oriented. As a multi-disciplinary field, CSCL papers bear more of a "family resemblance" (Wittgenstein, 1953) to each other, sharing diverse constellations of characteristics and relationships, rather than fitting a definition with necessary and sufficient conditions.

Perhaps that is why the first definition of CSCL (Koschmann, 1996) presented it as a "paradigm," contrasting it with earlier educational-technology research paradigms like computer-assisted instruction, intelligent tutoring systems and constructionist exploratory environments—which all focused on learning by individuals, conceived in terms of behaviorist, cognitivist or constructivist psychology, respectively. However, Koschmann (2001) soon realized that actual CSCL research did not form a neat paradigm, contrasting with earlier, incommensurate research approaches, but included an eclectic mixture of mutually conflicting theories, methods, pedagogies and settings.

A frequently cited introduction to CSCL (Stahl, Koschmann & Suthers, 2006) characterizes its approach as: "studying how people can learn together with the help of computers." This generic characterization is immediately followed with the warning that CSCL "has a complex relationship to established disciplines, evolves in ways that are hard to pinpoint and includes important contributions that seem incompatible." It suggests that one should "view CSCL as a vision of what may be possible with computers and of what kinds of research should be conducted, rather than as an established body of broadly accepted laboratory and classroom practices."

It seems that what we need is neither a definition of past work nor a paradigm of an ideal science, but a focused yet open vision for the future—along with a concrete "prototype" example to serve as a cognitive reference point (Lakoff, 1987). Therefore, I will here sketch a vision of CSCL based on my own efforts to develop a prototypical CSCL design. In addition, I will consider a selection of papers published in *ijCSCL* that I feel have until now been undervalued in setting future directions for CSCL.

The vision of CSCL advanced here is that students working in small groups can productively incorporate collaborative learning centrally in their schooling and in their intellectual development, taking advantage of appropriate forms of computer support. As CSCL is adopted as a foundational form of learning in educational systems around the world, students will acquire collaborative group practices, individual cognitive skills and technology-enhanced abilities to enable them to address the challenges of contemporary social issues.

Collaborative learning is a primary form of human learning, and facility in collaborating can enhance student participation in other learning. Meanings and practices developed by small groups can result in understandings and skills of the individual group participants—although the correspondence between learning at the different levels is by no means direct or necessary. Students and others can form spontaneous, opportunistic or long-term networks to discuss, debate and explore topics of interest—including issues of global importance; students can learn to build knowledge together and refine understanding by sharing perspectives. Formal education in schools can involve mutually supportive mixes of individual, small-group, classroom and networked activities.

Although knowledge has always been a social product in many senses, the ubiquity of computers and networking tremendously expands the potential to collaborate in building knowledge, to take advantage of computational support for knowledge creation, or to share and preserve knowledge. On the other hand, the proliferation of technology has also contributed to enormous societal problems: climate change, income inequality, over-population, fake news, nuclear proliferation and political schisms. The skills acquired during CSCL sessions in working, problem solving, conceptualizing and reflecting together in small groups may be critical for addressing such pressing social issues of our times.

Two major sources for CSCL theory are Vygotsky (1930/1978) and Lave and Wenger (1991); they proposed influential perspectives on mediated cognition and social practices—i.e., shifting the traditional focus from methodological individualism (including positivism, behaviorism and cognitivism) to the mind-in-society mediated by artifacts, and the community-of-practice as the primary level of analysis. Two early investigations following these perspectives and definitive of the CSCL vision were those of Scardamalia and Bereiter (1996) and Teasley and Roschelle (1993); they extended the unit of analysis to the group or classroom and to the joint-problem-space as represented by knowledge artifacts and as observable in shared discourse. These initiatives have been conceptually elaborated in subsequent CSCL theoretical papers, as we will see in the following.

My prototypical example of computer-supported collaborative learning involves a team of three 13-year-old girls interacting in the Virtual Math Teams (VMT) online environment to investigate dynamic geometry. The software allows a team of students to explore mathematical tasks in a shared dynamic-geometry workspace, which responds interactively to their actions constructing and dragging points, lines, triangles, and so on. The student discourse takes place through textual chat in the same environment. Tasks from the teacher and curriculum displayed in the workspace include example constructions, technical terminology and prompts for collaboration and discussion. The analysis of the team's eight hours of interaction (Stahl, 2016a) is carried out at the small-group unit, documenting how the team adopted over 60 "group practices" (Stahl, 2017) of collaborative interaction, geometry construction, problem solving and mathematical discourse. Without speculating about what took place in the individual students' minds, the analysis shows how the team achieved impressive geometry accomplishments as a group and documents that each individual significantly increased her geometry skills through participation in the collaborative learning.

This example prototype is specific in many ways: The team is a small group of students meeting online in an after-school club. It interacts through chat and actions in a multi-user application (see Figure 1). Pedagogical guidance is supplied by a carefully crafted sequence of tasks. Interaction in the group takes place as mediated by reference to the task descriptions, previous chat postings, construction actions and graphical figures. Analysis tracks the sequentiality of chat and math events as they develop within a network of artifacts, meanings, questions, technical terminology (e.g., "dependency") and practices (e.g., dragging points to test for dependencies). Learning Euclidean geometry has served since Plato as the classic gateway to logical thinking and deductive argumentation (Stahl, 2013; collaborative, computer-supported dynamic geometry could similarly serve as a training ground for the group cognition required for democratic responses to contemporary social issues through deeper understanding of interconnections among actors and factors.

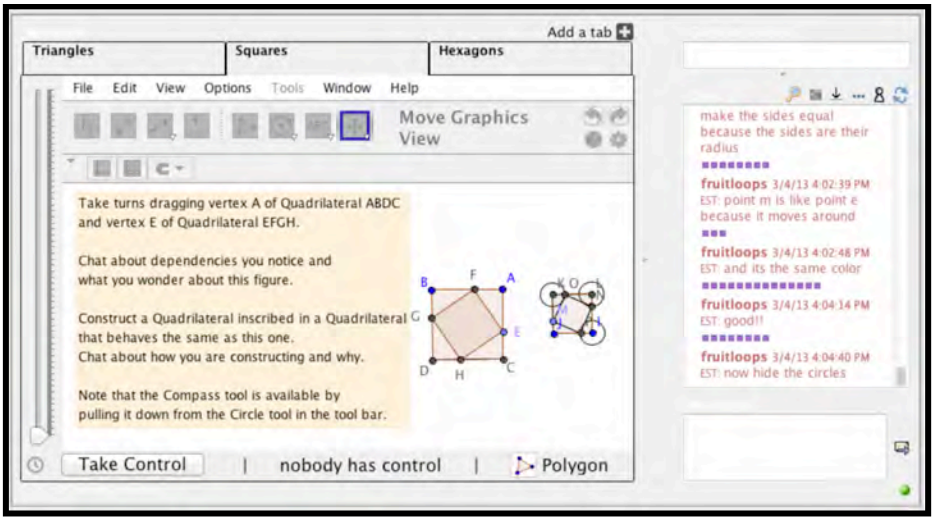

Figure 1. The VMT interface. The team has constructed square IJKL and inscribed another square inside it, based on exploration of the given example of square ABCD and past group experience constructing inscribed triangles.

Each of this prototype's specifics could be expanded by other CSCL efforts with family resemblances to it. Synchronous text chat can be replaced by asynchronous discussions, perhaps increasing reflection but lessening the flow of thinking together. Other knowledge domains can be supported with appropriate tools and curriculum. The role of computers in collaborative knowledge building can switch from communication medium to face-to-face workspace or embodied virtual reality. The after-school math club can grow to international networking, bringing different cultures together. CSCL environments can include scientific models, simulations or artistic media. They can be supported with feedback and analytics of the interaction for student awareness, teacher overview and researcher analysis.

The following consideration of several evocative papers in *ijCSCL* suggests possible dimensions for fruitful advances in the scope of CSCL from a focus on the micro-level interaction within small groups of students.

Extending the CSCL vision

In the first year of *ijCSCL* publication, **Jones, Dirckinck-Holmfeld and Lindstrom (2006)** [Investigation 3] proposed dramatically broadening the concerns of CSCL to include the larger socio-technical context and infrastructure. These authors argue for a relational, indirect, meso-level approach to CSCL design, which would go substantially beyond the traditional paradigm of educational studies. In this approach, the phenomena at the micro level are understood as outcomes of processes of development within their larger contexts.

Most educational research aims at objective results based on a view of the world as having fixed characteristics: it is assumed that technologies have inherent affordances, individual utterances have definite intended meanings, subjects have rational thoughts (logically connected mental representations), and analysis can be carried out algorithmically. Investigation is conducted at the individual unit of analysis, classifying student utterances as expressions of imputed intentions of individual speakers.

The paper by Jones, Dirckinck-Holmfeld & Lindstrom takes a very different tack. It proposes that affordances of CSCL technologies should be understood in terms of how they are taken up by users in the interactions that the technologies mediate. Meaning is here seen as an intersubjective product of the interaction among multiple people within their conversational context, including its technological artifacts and infrastructure. The concern is with the unfolding process of meaning making within these settings, rather than in traditionally conceived learning outcomes.

Analysis in this approach is complex, viewing each aspect of task, technology, personality, role, utterance, response or knowledge as inter-related or relational. Data is not directly determinant, but negotiated by participants and necessarily interpreted by researchers who understand colloquial language and human interaction. Furthermore, analysis of CSCL interactions is understood on many interpenetrating levels: the micro level of individual utterances and brief interactions, the small-group level of interacting teams of learners, the classroom level of teacher-led instruction, the local-culture level of schooling, the global level of geo-political and historical influences. Such multi-faceted analysis requires computer-supported collaboration among the multidisciplinary researchers themselves; it is notable that this paper was written by authors from three different countries.

The meso level of the community points to the realm of social practice as the locus within which interactional processes are situated; the social practices are taken up in small-group activity. This focus corresponds to the "practice turn" in contemporary social theory (Schatzki, Knorr Cetina & Savigny, 2001). In a practice-oriented analysis, structures are emergent; they grow out of recursive interactions among people, technologies and social action. In this post-cognitivist view (Stahl, 2016b), it is not mental representations in individual minds or designed properties of technology that directly structure the practice. Rather, it is through a recurrent and situated practice over time—a process of enactment of a relevant practice by a group—that people constitute and reconstitute a structure of technology use.

CSCL designers have only limited direct control over how their designs are actually used by students. How learners respond to, understand and enact artifacts in relation to any educational design is a complex structuration process that has to be studied in practice. The paper's authors contend that the CSCL tradition has pursued a relatively narrow focus that places in the background issues concerning the politics, policies, institutions and infrastructures in which the processes of CSCL take place. They argue for a greater inclusion of what they call the meso level of collaborative learning, as opposed to the trend towards networked individualism—the conception of collaborative groups in terms of their individual members. They asked—already back in 2006—whether CSCL, and education more generally perhaps, should act as a critical opponent to some of the trends identified in the networked society and stand up against networked individualism.

Several books published in recent months highlight the acute and growing importance for the survival of modern society of issues at the technological meso level or the knowledge infrastructure. Collaborative learning could prepare students to address such issues in the future, if CSCL develops effective appropriate interventions.

Climate change and ecological corrosion is one such issue of widespread concern. In his last major book, **Latour (2017)** argues that the unforeseen consequences of industrialization have transformed our relation to the natural world in a threatening way. What is needed is not a set of technological fixes, but a re-conceptualization of the distinction between nature and society. Not only are the new-age strictures about living in harmony with Mother Earth inadequate, but even the metaphors of ecological science need to be rethought. The complexity of climactic trends involves networks of interactions among countless human and non-human actors. The analysis of these interactions requires collaborative knowledge building on a global level, as does the designing of effective responses.

CSCL curricula can acculturate student teams to such knowledge building on a novice scale. CSCL software like Knowledge Forum, VMT and argumentation-support apps provide illustrative forms of computer support. For instance, many lessons in classrooms around the world using Knowledge Forum (Figure 2) already focus on group theorizing about environmental phenomena and historical conflicts; the geometric dependencies explored in VMT provide a metaphor for team thinking about interdependencies affecting the climate; argumentation-support systems model the forms of discourse needed for meaningful and democratic discussion of climate policy.

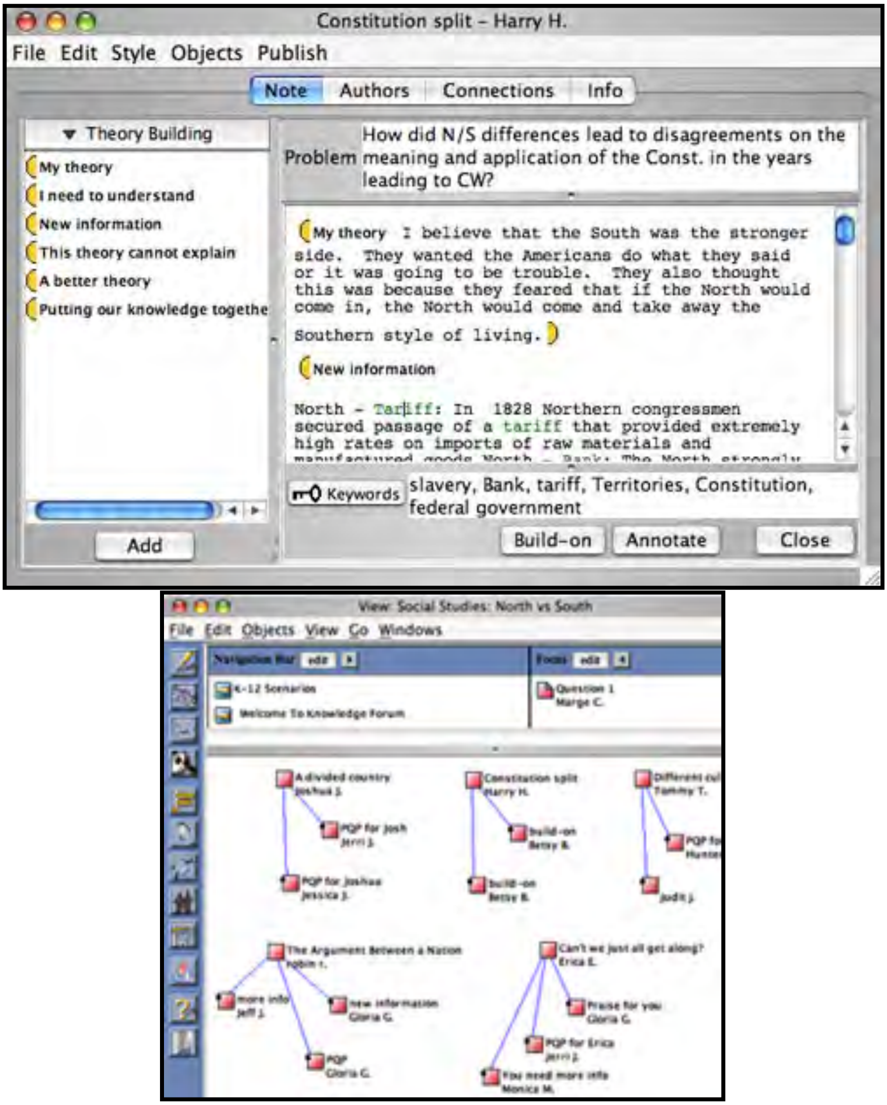

Figure 2. Knowledge Forum interface. Students enter theory-building notes (left). A view of interrelated notes is displayed graphically (right).

Computer technology—such as social media—provide a powerful infrastructure role in our society, including influencing the economy and politics. **Ekbia and Nardi (2017)** suggest that the very nature of capitalism is being transformed as people turn to online sources of information generated by unpaid participants. Companies can produce new products without having to supply manuals and training, as these are provided by the public through YouTube videos and product reviews. Other corporations provide information services through apps like Siri, Google, Alexa or FaceBook, which rely on volunteer-generated information like Wikipedia and the WorldWideWeb. This shifts labor costs from corporate wages to the unpaid public—from the producer to the consumer. Economically, this can be seen as a new strategy of capital to reduce its production costs. Consumer inputs are monetized by software giants like FaceBook and Google for use by corporate and political targeting.

The pervasive technological infrastructure of social media also plays a central role in the production and dissemination of "fake news," leading to the chaotic and simplistic character of public comprehension of the political world. **Rushdie (2017)** provides a sense of some of how this emerged with the Trump campaign. The modern-world ideals of rational thought, reasoned discourse and graspable truth seem to have dissolved in a flash. Training in thoughtful group cognition and deliberative argumentation may be the best antidote to the destructive "group-think" of emotionally charged political bubbles.

CSCL research has explored argumentation-support environments (as illustrated in Figure 3) to accustom students to logical debate, to teach them to view social issues from multiple perspectives and to discuss controversial topics through discourse platforms that support rational argumentation. These systems are often designed based on Toulmin's popular theory of argumentation structure. However, as **Schwarz and Baker (2017)** make clear, the Toulmin (1958) model is most appropriate for legal briefs; it does not apply to deductive mathematical proofs or to scientific hypotheses, let alone to informal debates, which feature emotion, prejudice, identity politics and power relationships. The book by Schwarz & Baker reviews in detail traditions of multiple world cultures that led to the potential of deliberative discourse as a basis for informed democracy. Such deliberation in small groups of students can prepare them to make sense of the world and to negotiate equitable shared understandings. Skill in conducting reasoned discourse and collaborative knowledge building is the only antidote to the spin of fake news and the blinders of emotionally charged political bubbles. Students need to internalize critical debate practices in order to evaluate online information analytically.

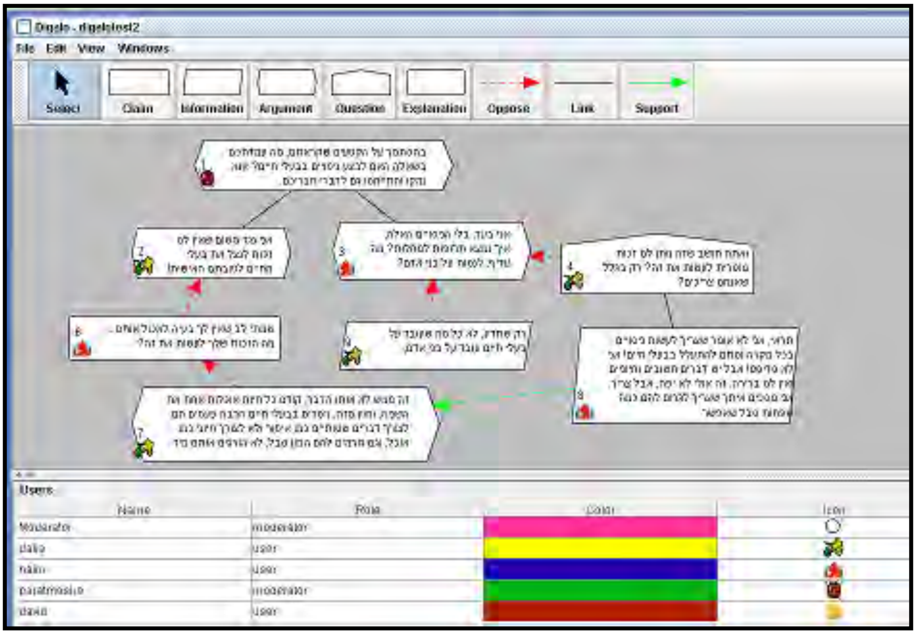

Figure 3. The Digalo interface. Students contribute elements of an argument and represent their role in the overall structure of the argument.

Conceptualizing the CSCL vision

A number of *ijCSCL* papers make important contributions to a conceptual framework for the extended CSCL vision suggested above.

Another paper from *ijCSCL*'s first year proposed an analytic focus on intersubjective meaning making. **Suthers (2006)** [Investigation 4] claims that to study the accomplishment of collaborative learning we must necessarily study the practices of intersubjective meaning making. In contrast to individualist epistemologies, where the individual is the learning agent, in intersubjective epistemologies the group is the learning agent. Collaborative knowledge construction locates the meaning making in its group context; the process of meaning making is itself constituted of social interactions. In CSCL, even if we ultimately want to track learning by individuals, we need to understand the processes of learning highlighted by intersubjective epistemologies, at both the interpersonal (group) and social (community) levels.

Meaning making in CSCL environments generally involves reference to representations, such as icons, words and drawings. Jointly constructed representations become imbued with meaning for the participants by virtue of having been produced through an interactional process of negotiation (discourse aimed at a consensual conclusion). These representational constituents then enable reference to prior interpretations with deictic pointing (through gesture or language), or by direct manipulation in a digital environment. In this manner, collaboratively constructed external representations facilitate subsequent negotiations—increasing the conceptual complexity that can be handled in group interactions and facilitating elaboration of previous conceptions. The expressive and indexical affordances of a technological medium affect its value as a referential resource.

The notion of referential resource is further elaborated in terms of practices and usage by **Zemel and Koschmann (2013)** [Investigation 5]. They analyze how a group of students in a VMT session specify how they understand the mathematical problem they are given on the computer screen and what for them might count as a solution to that problem. The authors focus on referential practices, understood as the ways that actors refer to and represent problems and solutions. References are indexical, that is, dependent on the circumstances of their occurrence for their local sense or meaning; they point or index into their context of production.

Math problems, for instance, are indexical phenomena that can be indexed in various ways. Students constitute the problem on which they are working by indexing it, pointing to it, referring to its constituent properties, elements and features in particular ways. (E.g., a line "looks perpendicular," it forms a right angle, it was constructed to be perpendicular.) The more refined their referential work, the more developed their understanding of the problem.

If some object or matter is something students communicate about and work with, they must have a set of shared interactional resources that allow them to refer to that object or matter in mutually intelligible ways. Thus, collaborative learning necessarily and centrally involves the interactional, shared construction of intersubjective meaning using referential resources. (See also Garfinkel (1967); Stahl (2015)).

The paper by Zemel & Koschmann details the work of problem solving as involving referential practices. It shows how when students in the VMT session build a representation of a problem in a particular manner using some combination of text and graphics, the key to meaning making is not the representation per se. It is the process of building the representation and working with it in a way that allows for the selection and identification of its relevant indexical properties. (This may explain the intriguing paradox of "productive failure" in CSCL groups (Kapur & Kinzer, 2009) [Investigation 14]. The specific indexical or referential properties of a math problem emerge through the way in which whiteboard objects and text postings are sequentially produced in relation to each other.

The idea that the meaning embodied in representations and other artifacts is interactionally constructed as a group repeatedly uses them is also explored by

Overdijk, van Diggelen, Andriessen and Kirschner (2014). They refine the concept of affordance (Dohn, 2009) by arguing that a technical artifact's potential for action only becomes available when learners and artifact connect, and that the availability and realization of this potential is relative to the students who interact with the artifact and to the socio-cultural context in which this takes place. When a group uses an artifact, the meaning of the artifact for the group undergoes a process of "instrumental genesis" (Rabardel & Bourmaud, 2003), in which the artifact is taken up in a specific way by the group, determining its possible significance for the group. To evaluate an innovative CSCL technological artifact, one must observe how it is used in practice. This implies a methodology of design-based research (DBR) and the identification of adoptions of group practices, as discussed below.

How a CSCL artifact is brought into use, or appropriated by students, involves a tension between the artifact as it is used by students and the intentions invested in the artifact by the designers or teachers. This tension may develop within a brief period in the context of joint activity, and be eventually resolved through a complex set of group negotiations. The effective affordances of CSCL technology result from the interaction of the implicit intentions invested in the artifact by instructional designers and the active intentionality of the learners who perform actions upon the artifact. In this way, utilization of a technical artifact can be seen as a process of social construction that is generated through a dialectic of resistance and accommodation between human agency of the student group and material agency of the designed artifact.

When groups bring an artifact into use, they call upon sets of routines and procedures that have developed around previous use of that artifact or similar artifacts. In other words, the use of artifacts is situated in group practices and motivated by routines and procedures that have become sedimented in those practices. The set of group practices incorporates resources for communication as well as classroom norms, procedures and other available technical artifacts. The group practices adopt and adapt specific social norms of the classroom that are relevant to the task at hand, and the social practices that have formed around this task. Overdijk et al. describe the appropriation of an artifact as meaningful by a group that is using that artifact as a series of enactments whereby social norms and group practices become gradually associated with the artifact. Such appropriation is framed within the constraining and enabling conditions of the local situation; through it, the group produces new conditions, affordances, meanings and understandings for future learning and action.

The idea that artifacts are brought into use and thereby granted specific meaning through the enactment of group practices is re-conceptualized at a global level of human evolution by **Ritella and Hakkarainen (2012)** [Investigation 7]. At the same time, they reflect on the difficulties of implementing appropriate educational responses implied by this new conceptualization. Key to both their theoretical and practical considerations is the concept of "knowledge practices." Knowledge (or epistemic) practices are defined as routine (recurrent and appropriated) personal, group and social activities related to working with existing knowledge and creating new knowledge. They include deliberate efforts to expand available intellectual resources by creating and building epistemic artifacts—symbols, concepts, technical terms, theories, inscriptions, visualizations, models, tools, etc.—which contribute to extending and preserving group knowledge.

Human beings do not have sufficient innate cognitive capacities to engage in the development of complex ideas within their individual brains; in order to pursue complex trains of thought, they have to, for instance, work on paper. Inscription and visualization allow human beings to establish a theoretic culture by gradually accumulating a wide variety of external symbolic storage systems. Experts can then internalize complex reasoning and memory capabilities through sustained habits of externally embodied cognitive practices. A crucial role in the evolution of our civilization was the emergence of external memory fields (lists of numerals, art, diagrams, writing, maps, spreadsheets, wikis, networked webs) that allow us to use our powerful visual system for elaborating, sharing and building on externally represented ideas and creating exponentially growing external symbolic storage systems. In this way, human biological evolution over epochs has been extended by much more rapid cultural evolution (Donald, 1991; 2001), now amplified by technological evolution.

CSCL environments are designed to support the collaborative building of knowledge through construction of knowledge artifacts, which constitute locally created cognitive-cultural networks and mediate knowledge building. However, these goals must be brought into practice by students using them. Learning to engage in knowledge building requires the deliberate transformation of classroom-learning activities and student-participation routines, in order to capitalize on the potential epistemic mediation designed into these external artifacts. CSCL technologies allow for delegating cognitive processes to digital systems, creating mechanisms for fusing intellectual efforts in collaboration, and complementing personal epistemic resources with global networks that are accessible online. The vision of CSCL is to take advantage of forms of media in a way unthinkable in the past. Rather than examining digital artifacts as merely isolated tools and signs, we should examine how they might radically transform human cognition and activity.

Conventional education focuses mostly on using the Internet for acquiring and consuming, rather than for creating knowledge. By contrast, CSCL creates foci around which collaborative knowledge-building practices can be organized. Such environments could provide the material agency that enables even elementary-school students to participate in deliberate knowledge advancement, with adequate guidance and facilitated by teachers. The current textual practices prevailing at school, however, often guide students to use writing mostly for reporting what their textbooks say about issues being studied rather than using writing as a tool for extending thinking and deliberately generating new ideas and working theories. Adopting and cultivating a cognitive-cultural system that enables effective use of writing as a tool of thinking is difficult; it is an extended struggle to acquire embodied, largely tacit capabilities rather than direct assimilation of well-specified skills.

The CSCL vision involves educating students for future forms of cognition: technology-supported and collaborative—in groups and globally. The potential of human cognition continues to expand dramatically, and CSCL can help prepare students to appropriate the required practices and modes of learning. However, technological artifacts become instruments of human activity only through sustained and iterative efforts of using them in practice, a process through which cognitive-cultural activity gradually transforms and adapts according to evolving practices of using technologies. This evolution is reflected in deep-level changes in mental processes. Unfortunately, this must overcome considerable resistance and inertia. This is clear in the fact that it is still rare for students to appropriate the full potential of the written word after millennia of literacy (Ong, 1998). Not surprisingly, CSCL researchers have generally underestimated the in-depth challenges associated with students enacting new cognitive practices at the personal and collective levels.

Ritella & Hakkarainen argue that all successful cultures of CSCL are simultaneously also expansive-learning communities (Engeström, 1987) focused on problematizing current practices, envisioning changes and gradually, step-by-step, consolidating novel inquiry practices. Through sustained collaborative activity, ideas, artifacts, methods and practices—that do not belong to any one of the individual participants—emerge situationally and interactionally within groups from self-organized collaborative processes as meaningful and effective.

The expansion of the vision of CSCL with theoretical elaboration of concepts like intersubjective meaning making, referential resources, instrumental genesis and cultural evolution prepares the way for understanding how CSCL in the future could contribute to intellectual development of new generations. The problem becomes a more practical one of evaluating the potential impact of proposed innovations. How can these theories guide the CSCL design process?

Analyzing the CSCL vision

The conceptual framework discussed in the previous section has implications for CSCL methodology. It means that it is no longer sufficient to run simple controlled studies with some student groups using an experimental CSCL tool and the other students not using it—and then concluding that if the students in the experimental condition individually tested higher, then:

The new CSCL tool led to more learning;

The tool worked as designed; and

Collaborative learning is effective.

Rather, the theory suggests, for instance, that:

Collaborative learning is a complex process that is in each case situated in specific group contexts and requires meaning-making interactions;

CSCL tools must be appropriated by user groups over time to determine their affordances; and

CSCL environments ultimately aim at expanding the power of human knowledge building by providing artifacts that extend external memory, computational ability and conceptual depth.

Analyses of interventions with new CSCL tools need to explore how teams of users take up—or fail to appropriate—the designed artifacts as knowledge-building tools. This generally involves scrutinizing:

The discourse and actions within the team of students as it constitutes the team's intersubjective meaning making,

The instrumental genesis of CSCL tools as used by the team, and

The team's adoption of group practices associated with the CSCL approach and resources.

A number of *ijCSCL* articles in the past address aspects of the methodology required to accomplish such analysis of CSCL interventions.

The focus on student discourse is perhaps the primary consideration. This is motivated by the theory of "commognition" (communication-based cognition). **Sfard (2008)** proposed that human cognition (thinking) is a derivative form of communication (speaking). Young children first learn to talk in family interaction, later engaging in self-talk, which eventually evolves into silent thought (see Vygotsky, 1930/1978; 1934/1986). Language was the first step in cultural evolution, leading to cognition by nomadic hunting teams, extended-family tribes and eventually individuals. Commognition incorporates the response structure of interacting multiple voices even in an individual's solitary reflection (Bakhtin, 1986). In CSCL data, the sequential nature of discourse can be made visible in the structure of external-memory artifacts, including captured transcripts. Techniques of sequential analysis can be adapted to CSCL from Conversation Analysis, as systematized by Schegloff (2007), analyzing how utterances evoke and respond to each other in interactional processes of intersubjective meaning making, group cognition and collaborative knowledge building.

Sfard's book was reviewed in *ijCSCL* (**Stahl, 2008)** [Investigation 8]. It emphasizes how mathematical cognition can be conceived of and analyzed as particular discourses. How children come to participate in these discourses and individualize the dominant social language of mathematics into their personal math thinking involves discursive social processes—not rote acquisition of memorized facts, but participation in co-construction of realizations (representational resources that index mathematical terms and figures). Sfard conceives this as participation in social routines. Routines are meta-level rules that describe recurrent patterns of math discourse. Like Sfard's discussion itself, routines describe mathematical discourses rather than math objects. She describes in some detail three types of routines: deeds, explorations and rituals. Deeds are methods for making changes to objects, such as drawing and enumerating squares on a digital whiteboard. Explorations are routines that contribute to a theory, like a student's proposal. Rituals are group practices that maintain the flow of social activity, like questioning and taking turns.

Learning mathematics can be conceptualized as participation in a discourse in which people engage in the social construction of math objects. In collaborative learning of math, groups of students adopt group practices that mirror social practices of the mathematics tradition as they explore math problems, propose solutions and gradually employ technical terms. Through such participation, individual students can understand and personalize elements of the discourse.

Deep knowledge does not consist of memorizing discrete facts. There is not a single meaning of an equation or a theorem, but a network of interrelated potential realizations. To deeply understand the object, one must be conversant with multiple such realizations, be competent at working with them, be cognizant of their interrelationships and be able to recognize when they are applicable. This implies that evaluation of learning should not consist of testing individual memories, but of observing the application of key practices.

Consider the concept of perpendicular bisector and its construction in Euclidean geometry. **Öner (2016)** [Investigation 9] analyzes how a group of students enrich their understanding of this math object during a session in the VMT environment. She employs Sfard's commognitive framework to examine how the student team's word choice, use of visual mediators and adoption of geometric construction routines changed their character during an hour-long collaborative problem-solving session. Her findings indicate that the team gradually moved from a visually oriented discussion toward a more formal discourse—one that is primarily characterized by a routine of constructing geometric dependencies.

Öner's particular analytic focus is on the changes in: (a) the team's use of the word "perpendicular," (b) the visual mediators the team acted upon (i.e., the example perpendicular bisector in the workspace), and (c) their mathematical routines, since the shifts in these features were the most salient aspects of their changing discourse. The study investigates two routines:

The production of the perpendicular: This routine was gradually altered from drawing by visual placement to construction by creating dynamic-geometry dependencies.

The verification of perpendicularity: This routine for substantiating whether a line is in fact perpendicular to another line shifted from visual judgment or numerical measurements to use of theoretical geometry knowledge to justify proposed solutions.

Initially, the team's notion of perpendicular referred to a visual image. It evolved into one that represented a mathematical relationship based on defining dependencies. These transformations of discourse and of construction practices took place within the context of group interaction, enacting task instructions and interacting with the VMT software. The team's shift to increasingly abstract thinking corresponds to a major development in human cognition—both in the evolution of the species and in the intellectual maturation of the group or individual.

The way that actions and conceptualizations shifted during the hour of interaction involving perpendiculars highlights the importance of temporality in learning. An article by **Reimann (2009)** [Investigation 10] addresses the need for temporal analysis in CSCL research more generally. For both the sociocultural and the individual-cognitive views of learning, the nature of the learning process is temporal: learning unfolds over time. Because human learning is inherently cumulative, the sequence in which experiences are encountered affects how one learns and what one learns. This applies to the communication and interaction processes that take place in groups as much as in the silent reflections of individual learning.

Reimann contends that the quantitative, variable-centered method dominant in most experimental learning research makes restrictive assumptions on the kind of data useful for analysis and on the forms of causation allowed to explain change. Adapting a process-analysis approach focused on temporality and sequentiality provides an alternative, still rigorous method to analyze group processes. Temporal-event analysis can offer a methodological link between those researchers in CSCL who are producing descriptive, "thick," interpretive accounts of groups' computer-mediated interactions, and those who work experimentally and quantitatively. However, existing process models in CSCL, which predominantly describe short-term interactions, will need considerable theoretical extensions to connect with theories of longer-term change.

An example of temporal analysis is provided by **Damsa (2014)** [Investigation 11] in her examination of productive interactions. For her, "productive interaction" refers to knowledge co-construction within the context of a knowledge domain, entailing joint actions directed toward mutual goals, increased intersubjective understanding of concepts, and also actions that contribute de facto to the construction and progress of shared knowledge objects. The emergent epistemic (knowledge) objects are key to collaborative learning because they influence the course and productivity of interaction. The knowledge objects become both outcomes and mediating elements in the interactional process. Damsa's study finds that groups that manifest shared epistemic agency produce knowledge objects that are more complex and better suited to the problems addressed. More than technological artifacts, which are adopted as mediating instruments, a group's knowledge objects can remain problematic and open to transformation and further exploration by the group.

It is essential to define the nature of productive interactions: a) how they are different from other types of interaction and how they lead to knowledge construction; b) the temporality involved in the interaction; and c) the multiple analytic layers that comprise this process—including interactions, knowledge objects, agency and their interconnections. The unit of analysis is not the individual, but the joint action (verbal or otherwise) directed at the co-construction and elaboration of the knowledge objects involved—in other words, the mediated interaction. This mediation leads us to the combination of the productive interaction, the objects that variously mediate this interaction and the agency of the group as a construct of individual engagement and collective commission. The way these are woven together is intimately related to the temporality of the longer collaborative-learning process and to how these components combine while unfolding in time.

One distinctive contribution of Damsa's empirical examination is its attempt to follow, along with the unfolding interaction, the knowledge that emerges and gains shape through the interaction. This analysis focuses on the trajectory of the knowledge from the moment it enters the interaction process until it has materialized and is elaborated into the final objects produced by the groups. The productivity of the interaction manifests itself through the sequence of actions in the interaction that leads to the co-elaboration of knowledge objects. Organizing and attending to the sequential structure in which knowledge is not only generated and discussed but also taken up, elaborated upon and refined is of essential importance. Early versions of knowledge objects often play a catalyzing role in groups' extended interactions, influencing how interaction changes or adjusts with time, in order to become meaningful for the co-construction of shared knowledge objects.

Analysis of the temporal structure of interaction can take many forms. **Çakir, Zemel and Stahl (2009)** [Investigation 12] show how participants in a VMT session sequentially construct graphical animations of their shared mathematical representations in order to build intersubjective meaning. In order to collaborate effectively in group discourse on a topic like mathematical patterns, group participants must organize their activities in ways that share the significance of their utterances, inscriptions and behaviors. This case study investigates the moment-by-moment details of the interaction practices through which the students organize their chat utterances and whiteboard actions, highlighting the sequentiality of action and the implicit indexicality of the intersubjective meaning making.

A student constructed the whiteboard diagram of the stack of blocks in Figure 4 (left) by successively adding columns of blocks. The student first took the highest existing column and copied it to form an additional column, and then added an extra block at the top. The sequentiality of this construction process made the mathematical pattern clear to everyone in the group: that the number of blocks increases with each new column by the amount it increased with the last column plus one. This visual articulation of the structure to the pattern allowed the group to quickly derive its formula. Similarly, the array of hexagons in Figure 4 (right) is overlaid by one of the students with colored lines that first divide a composite hexagon like the outlined hexagon into six symmetrical sectors. Then the lines crossing one of these sectors are overlaid by lines of different colors. The sequentiality of drawing these lines makes visible and consequent the structure of short lines constituting a hexagon with sides of N units. Namely, there are 1+2+3+…+N units in each of the three directions within each of the six sectors. This visually observable structure leads the group directly to a mathematical expression for the number of unit triangles and lines for any size hexagon.

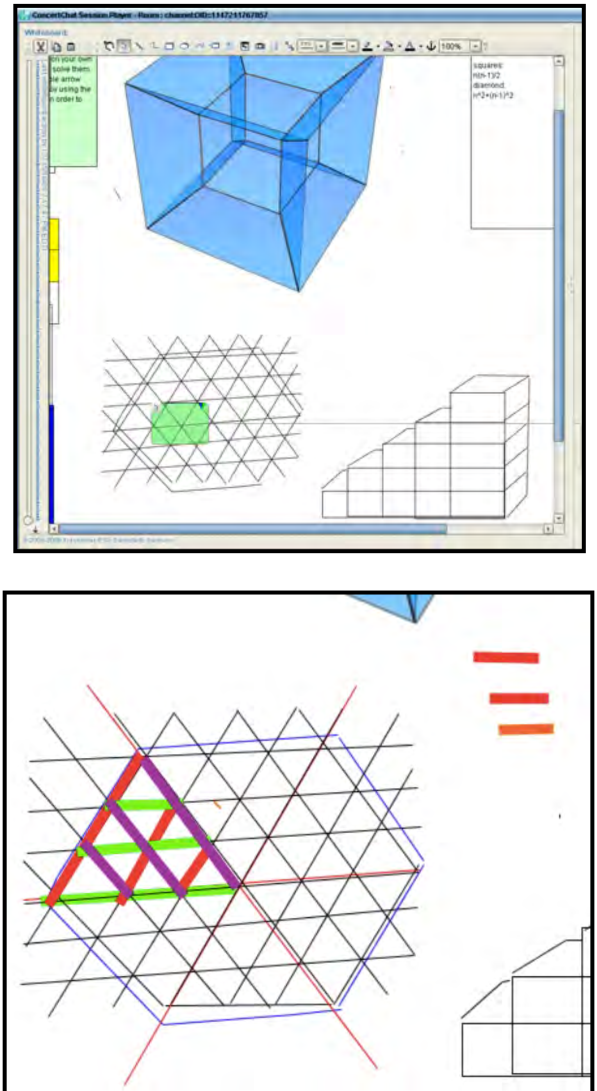

Figure 4. The VMT interface with a student construction of a hexagon array and of stacked blocks (left). Colored lines decompose a large hexagon into sequences of small triangles (right).

The sequential temporal analysis by Çakir, et al. treats the whiteboard as a kind of shared external memory or "joint problem space" (Teasley & Roschelle, 1993) where the group builds up, shares and preserves a record of agreed-upon facts, opinions, hypotheses or conclusions. Shared visible communication media like this can provide places where the group does its work—where it cognizes. Ideas, concepts, meanings and so forth can subsequently be taken up by individuals into their personal memories as referential resources for future social or mental interactions. There is no need to reduce group meaning to identical individual mental contents; the location of the group cognition and group memory is the discourse medium, with all its particular affordances and modes of access.

In another temporal analysis of collaborative learning in the same sequence of VMT sessions, Medina and Suthers (2013) identified a set of group practices that the student team adopted as representational resources. This included the use of colored lines to establish shared indexicality. The analysis was based on a detailed tracking of the development of several practices that individual students introduced to the team and were gradually adopted as shared group practices. Interestingly, the tracking of this development was done retrospectively, by successively following the usage backwards through the group sessions (Medina, 2013). It was also demonstrated that the practices were effectively shared in the end because each student was ultimately able to initiate use of each practice within the group interaction.

In these papers, the problem of common ground—controversial in CSCL—is re-conceptualized from an issue of converging personal mental representations (e.g., in Clark & Brennan, 1991) to a practical matter for the group of being able to jointly relate semiotic objects to their indexed referents. The references do not reside in the minds of particular actors, but have been crafted into the presentation of the chat postings and drawing inscriptions through the details of wording and sequential presentation. The references are present in the data as affordances for understanding by group participants as well as by researchers studying transcripts of the interaction. The meaning is there in the visual presentation of the communication objects and in the network of interrelated references, rather than in mental re-presentations of them. The understanding of the references is a matter of normally tacit social practices, rather than of rationalist explicit deduction (Stahl, 2006; 2016a).

The practices of the group are related to personal skills of the individual group members as well as to countless social practices established in the larger community or culture. For instance, the students brought in the mathematical practice of summing the sequence 1+2+3+…+N to the well-known summation expression (N+1)/2. On the other hand, the practice of overlaying colored lines on a whiteboard diagram had to be explained by one student to the others, who did not know how to select colors for lines. Both of these practices were adopted by the team, then understood and used repeatedly by all team members as "group practices" [Investigation 19] contributing to productive interaction.

The considerations about analysis and evaluation of CSCL interactions discussed in this section indicate how to address the theoretical views of collaborative learning presented in the previous section:

Analysis focuses on the group discourse and actions as contributing to intersubjective meaning making,

The temporal development of the group's use of tools, terminology and referential resources is followed closely, and

The team's adoption of group practices—which may contribute to group members' individual intellectual development—is tracked and documented.

It seems that CSCL research may be on the verge of fostering significant, urgently needed development of human cognition through the design of instruments of collaboration or external memory and by promoting the acquisition of associated group practices that exploit those tools in productive ways. Then the next question is how we can proceed to disseminate the early successes, innovative approaches and timely visions of CSCL. There is no point in waiting for some technical perfection of the field, for maturity will only come with experience meeting authentic needs in genuine educational circumstances.

Delivering the CSCL vision

CSCL is advanced through pioneering forms of computer support, as well as theoretical and methodological innovation. Many CSCL research labs have focused on the development of new forms of computer support and/or the design of online environments to foster collaborative learning. This book is not the place to review such efforts, as important as they may be for transforming theoretical understanding of collaborative learning into practical efforts to promote and sustain knowledge building within student groups. However, three rather diverse examples of innovative pedagogical design are included to illustrate inventive ways to extend the CSCL paradigm:

Schneider and Pea (2013) [Investigation 13] explore the use of eye-tracking hardware in an online collaboration environment. The traces of where the participants' eyes are looking can be made available to the students themselves in real time, as well as to researchers retrospectively. When the students see where their partners are looking, they adjust their own visual attention. This can enhance joint attention. Just as we saw in Investigation 12, joint attention can be required for productive collaboration. This component of shared understanding and intersubjectivity will be discussed at length in the later theoretical and philosophical investigations. Access to eye-tracker traces for CSCL researchers can be useful for formulating objective measures of common ground.

1. **Kapur and Kinzer (2009)** [Investigation 14] discovered one of the most intriguing results of CSCL experimental research. They determined that

allowing collaborating student groups to struggle and even fail at tasks that are ill-structured and beyond their skills and abilities may be a productive exercise in failure. They may develop relevant group practices of problem solving that are useful in subsequent efforts, whether collaborative or individual. This discovery has implications for sequencing the presentation of problems and challenges for collaborative work—an important but subtle part of CSCL curricular design. The efficacy of failure also problematizes the traditional approach to testing the short-term success of individuals.

Chen, Scardamalia and Bereiter (2015) [Investigation 15] provide a new feature within Knowledge Forum for classes to promote what the students identify as "promising ideas." This provides support for the group to reflect upon directions to pursue in their own collaborative discourse. This feature appears to be a promising idea for extending this popular software, even for use by students as young as 8 years old.

As emphasized above, new technologies and curricular interventions need to be tested, investigated and developed in realistic settings. Designers need to see how groups of students use and enact the designed objects. Simple pre/post tests of learning effects are not generally adequate, although they may play useful roles within the larger research context. Sequential analysis is often necessary to see how student teams make intersubjective meaning through the mediation of the designed artifacts and how they produce knowledge objects over time. Identifying the adoption of group practices may inform and even guide this analysis.

Design-based research (DBR) is widely recognized in CSCL as a common approach to technology design. This provides a research structure for observing how student teams take up the intended affordances of innovative technology, pedagogy and curricular resources. Unfortunately, there is no corresponding accepted methodology for evaluating the performance of designs as they go through iterations of testing, evaluation and redesign. This is where the focus on intersubjective meaning making, referential resources, instrumental genesis, epistemic objects, temporal sequentiality and adoption of group practices is needed. Nevertheless, even once one has determined that a CSCL innovation has been adequately refined, there is still much to do to put it into widespread practice.

Key to delivering the CSCL experience to students in a systematic way is involvement of qualified teachers. As illustrated in this section, each of the major efforts so far to implement CSCL in schools has emphasized teacher preparation. Experience has shown that CSCL requires a classroom culture of collaboration. Establishing such a culture requires the leadership of experienced teachers, who know how to guide student discourse and encourage student agency without being invasive and interfering in the collaborative interactions themselves. It generally takes at least three years for even a motivated early adopter teacher to transition from leading a teacher-centric classroom to facilitating a collaborative-learning one.

The VMT project offered teacher-professional-development credits in teaching collaborative dynamic geometry through the Math Forum and masters level courses at Drexel and Rutgers-Newark Universities for in-service mathematics teachers. In these courses, teachers participated in the same VMT curriculum as their students would later use, although the teacher discussions included pedagogical issues as well as a more sophisticated mathematical discourse (Alqahtania & Powell, 2017).

In Singapore, Hong Kong, Canada, Finland and other countries in which CSCL has been introduced into school systems, teacher training has always been the emphasis. Researchers worked with individual teachers over extended periods, and early adopter teachers served as mentors for other teachers in their schools. The most commonly used CSCL technology in these countries has been Knowledge Forum. **(Bereiter & Scardamalia, 2018)** comprehensively review all major aspects of this technology and pedagogy, including teacher preparation. The lead researchers in Singapore and Hong Kong have provided insightful reflections on their experiences as well, as summarized in the following.

In Singapore, the government legislated transformation of schooling to meet twenty-first-century cognitive needs. They established an academic research lab to plan, spearhead and evaluate this effort. The lab recruited CSCL researchers from around the world as staff and collaborators. Some of the leaders at that lab reflected on their approach in *ijCSCL*. **Looi, So, Toh and Chen (2011)** [Investigation 16] note that research supported by individual grants to researchers has produced interesting ideas and small-scale proofs of concept. However, when one thinks about transforming school systems, one sees that the CSCL tools are fragmentary and scattered. Putting together a coherent classroom program requires a variety of work that has not yet been done for CSCL. This requires a serious commitment from all concerned.

In Singapore, the authors report, there exists a combination of strong, explicit top-down directives and bottom-up desire for transforming and improving the educational system. Looi, So, Toh & Chen argue for design-based research as the methodological framework for designing and enacting school-based research that can impact school practices, as well as for refining theoretical understandings on how beliefs about the premises of CSCL are shaped and changed in the course of research implementation. They discuss their research innovations from a systemic-change perspective that includes the micro, meso and macro levels of educational systems. Their paper reviews: policy imperatives governing Singapore's educational landscape as macro-level actions; socio-cultural factors of the school's learning ecology as meso-level considerations; and contextualized classroom-based interactions as micro-level factors.

The Singapore educational national plan (adopted in 2008) explicitly foregrounds a central role for technology-enabled learning: to develop students to be collaborative learners. Significantly, it also recognizes the need to address the curriculum and assessment conundrum in order for technology-enabled pedagogical practices to really take off in schools. This was addressed through four major phases of systemic-change processes for sustainability at the macro level: 1) creation of readiness, 2) phasing of changes, 3) institutionalization and 4) ongoing evolution and creative renewal of the policies.

The Singapore effort to bring CSCL to scale in a (relatively small, culturally homogeneous) national school system addressed the complex interrelationship among teachers, school culture, leadership and educational policies. Effectively scaling up encompassed four interrelated dimensions: depth, sustainability, spread and shift in reform ownership. Depth refers to consequential change in classroom practice, altering teachers' beliefs, norms of social interaction and pedagogical principles as enacted in the curriculum. Sustainability involves maintaining these consequential changes over substantial periods. Spread is based on the diffusion of the innovation to large numbers of classrooms and schools. Shift requires districts, schools and teachers to assume ownership of the innovation—deepening, sustaining and spreading its impact. Beyond these dimensions comes evolution, in which the innovation, as revised by its adapters, is influential in reshaping the thinking of its designers and creating a community of practice that continues the innovation process.

Design-based research was iterated in selected Singapore schools, as researchers engaged in design of technology and curriculum, worked with teachers to enact the design in classroom settings, researched the contextualized learning processes, developed or refined theories of collaborative learning, engaged in re-design, and continued the cycle of re-design and implementation. With the realization that both teachers and students initially lacked the expertise to facilitate collaborative learning, the researchers and teachers co-designed many classroom sessions using a relatively simple CSCL tool, Group Scribbles. This digital Post-It-Notes technology allowed students to compose, share and compare notes with text and drawings.

A number of factors were key to eventual success:

Routine use was emphasized in the classroom from the outset. In the first school worked with, the teachers were supported for a period of 2 years in the routine use of the technology in weekly lessons. The routine practices helped alleviate the novelty effect of experiencing a new technology and the associated innovative pedagogy.

The technology was simple and easy to use. However, there was not a technology focus at the outset. Instead, enculturation opportunities were provided for the teachers and students to enact collaborative practices first, before using the technology.

Face-to-face CSCL technology was used in class to mediate student-student and student-teacher conversations, increasing the bandwidth of communication.

Design principles were adopted and refined to empower teachers to design collaborative activities. The objective was for the teachers to be ingrained with sound design principles for designing pedagogy, so that even without the use of CSCL technology, the teachers would incorporate notions of rapid collaborative idea-improvement in their teaching.

New lessons tapped existing curriculum, and thus were integral to the learning of the curriculum.

The lessons were co-designed by the teachers and researchers, providing ownership by the teachers of the lesson plans and resources. Toward the later part of the intervention, teachers were able to devise their own CSCL activities to share their experiences and lesson plans with teachers at other schools.

There was extensive professional development for the teachers, especially to help them orchestrate collaborative-learning activities in the classroom.

Going to scale involved systematic expansion, eventually leading to deeper pedagogical changes in teaching and learning practices.

Maintaining on-going dialogues between researchers and teachers was important so that schools could ultimately benefit from the enduring and synergistic alignment of policy, practice and research.

The effort to adopt CSCL in Hong Kong had a somewhat different approach, but many parallel lessons. **Chan (2011)** [Investigation 17] reports on the establishment of classroom cultures and communities of practice among teachers in schools and systems. She draws on experiences in Hong Kong and examines research-based CSCL classroom innovations in the context of scaling up and sustaining a knowledge-building model in Hong Kong classrooms.

Classroom innovations involve complex and emergent changes occurring at different levels of the educational system. The experience of CSCL knowledge-building classroom innovations in Hong Kong schools included research, interventions and teacher support at three major levels: the macro-context of educational policies and educational reform, the meso-context of a knowledge-building teacher network, and the micro-context of knowledge-building design in classrooms. At the macro level, the Hong Kong case study begins with educational reforms and the policies of the Hong Kong government that provided a favorable context for CSCL classroom innovation. At the meso-level, its focus is on how a knowledge-building teacher network supported teacher change towards classroom innovation. The study also addresses the micro-level classroom design to illustrate how principles, pedagogy and technology are integrated, considering the socio-cultural context, for example, the strong emphasis on examinations in Hong Kong schools. Three interacting themes—context and systemic change, capacity and community building, and innovation as inquiry—are proposed for examining collaboration and knowledge creation for classroom transformation.

The transition from micro-level case studies of isolated small groups using CSCL technology to whole school systems adopting the CSCL vision is challenging. Epistemological and cultural factors, such as student beliefs and the tradition of teachers working as individual (largely isolated and autonomous) professionals, are generally not congruent with research in learning sciences and CSCL. Organizational and school-level constraints make it very difficult for teachers to reflect collectively on their practices and engage in sustained expansive learning in CSCL environments. Furthermore, the current CSCL tools are limited and require surveying what is available; adapting it to the local conditions; setting up infrastructure; carrying out missing research; adopting long-term approaches to training and supporting teachers; and affecting a cultural change of public expectations, understanding and attitudes. These require massive funding for resources such as coordinated research, infrastructure, administrative support, training, teacher time for mentoring and textbook materials.

Addressing these barriers and needs, various teacher communities emerged in Hong Kong, some spontaneously and some supported by the government and universities. Through technological advances and CSCL research, a new kind of structure—a teacher network—emerged as a type of meso-level bridge from government policy via capacity building to classroom implementation. The Knowledge-Building Teacher Network—organized and supported by Chan's research group with national funding and commitment—initially focused on helping teachers to reflect on their pedagogical beliefs or practices, and to contrast them with the knowledge-building model of collaborative learning associated with Knowledge Forum software.

The teacher-network community played a central role in supporting change in Hong Kong schools. Research revealed that teachers go through different phases in adopting technology; communities of practice are useful for scaffolding and connecting technology use with principle-based understanding. One approach is to engage teachers in using technology in ways that are aligned with principles, pedagogy and assessment, thus affording them deeper insights. Teachers in the network were encouraged to contribute their reflections to community discussion-boards, to help them experience how technological affordances connect with pedagogy. Tool development for the assessment of knowledge building is not just for research analysis; the tools can be placed in the hands of teachers and students so that they might take agency to reflect on their work.

The key lesson is that researchers do not just ask schools and teachers to adopt pedagogy developed in other classrooms; they work together with teachers to create new usable knowledge. Co-inquiry and knowledge creation—not the imposition of ready-made innovation—is a central theme in designing and facilitating collaboration in professional communities. Within the teacher network, researchers and early adopters (often supported with paid leave from their classrooms to work with other teachers) collaborated with teachers new to the network.

One can consider such group teacher professional development as knowledge creation, with teachers working collectively to build shared knowledge. More broadly, a teacher network may provide a meso-level structure that coordinates and regulates macro-level political, institutional and cultural influences on micro-level classroom processes and student change. The Hong Kong researchers adapted CSCL discussion technologies to support the teacher network throughout Hong Kong. They also employed CSCL methods of discourse analysis to analyze the mezo-level interactions among teachers reflecting on their classroom experiences.

Singapore and Hong Kong are both special cases of national school systems under pressure to prepare a workforce for leadership in a technologically sophisticated global economy. It is striking that the results of the first PISA study of collaborative problem solving ranked Singapore number one and Hong Kong number three out of 51 tested countries in 2015, a couple years after the interventions reviewed here (OECD, 2017). PISA uses a very different methodology than what has been discussed here. However, the case studies by the Singapore and Hong Kong researchers demonstrate that propagation of CSCL approaches is possible in mainstream classrooms. Furthermore, their thoughtful reflections on the efforts in these countries provide multiple important lessons and recommendations.

Propagating the CSCL vision

In this Investigation, we have considered a vision of collaborative learning, illustrated by a prototypical research effort. The scope of CSCL was then extended in response to contemporary theory and current social issues, clarifying the distinctiveness and priority of intersubjective meaning making, instrumental genesis, epistemic objects and other theoretical and analytic constructs. These conceptualizations suggested approaches to evaluation of CSCL DBR interventions in terms of sequential analysis of discourse and adoption of group practices mediated by appropriated artifacts—filling a need for a suitable CSCL methodology. Examples of efforts in Singapore and Hong Kong to bring the CSCL vision to scale in educational practice were then reviewed. Now we need to consider how to realize this vision of CSCL more generally.

We begin by considering how our prototypical example of CSCL could have been scaled up for routine use in schools around the world. After 15 years of grants and collaboration with many international researchers (see Stahl, 2009), VMT had been developed to the point at which it established a proof of concept for the VMT vision and the associated theory of group cognition (Stahl, 2006), applied to collaborative dynamic geometry. The software was robust enough for classroom usage—in both desktop and mobile versions. A core concept of the domain had been identified: dependencies in geometric constructions. Corresponding to this concept, curriculum for introducing dynamic geometry had been developed through numerous iterations and had been used in trials with researchers, math teachers and students in and outside of school (Stahl, 2013). Teacher professional development had also been offered, using the same curriculum, supplemented with resources for teaching using collaborative learning.

It seemed clear that the VMT prototype could be scaled up. Dynamic-geometry software like SketchPad and GeoGebra are already used in many math classrooms worldwide, although without support for online collaboration or a systematic curriculum. VMT ported the free, open-source GeoGebra software to the VMT multi-user platform. The developers of GeoGebra would be willing to adopt and support this kind of multi-user version if they saw a broad demand for it. Their software is already used in 190 countries and translated into 52 languages. The Math Forum subsequently became part of the National Council of Teachers of Mathematics, an ideal dissemination center in the US. Thus, the technical infrastructure and access to individual teachers seems to be at hand.

The VMT curriculum was largely based on Euclid's original, orderly presentation of geometry and on the US Common Core geometry curriculum. It could now be further elaborated to tie into major textbooks so that online collaborative sessions could be held in conjunction with traditional lectures, textbooks, YouTube videos and homework assignments. Teachers could orchestrate the collaborative learning to serve different functions within math courses: exploration, challenge problems or roles that are more central. Teacher guides could be prepared, directing teachers how to modify, excerpt, extend or adapt the session presentations to their classroom contexts. The curriculum could also be developed for use in different cultures or countries, translating the approach as well as the language. Finally, additional curriculum could be written for other math topics—GeoGebra is designed for all middle-school, high-school and early college mathematics, not just geometry. Once students, teachers and schools have positive experience with collaborative learning or a given CSCL technology in one course, they are much more prepared and motivated to use it in other areas.

Similarly, other proven CSCL interventions—bearing family resemblance to the VMT prototypical example—could be scaled up to global adoption. One could, for instance, identify a core underlying concept of a selected domain to target or specify certain social practices that would be important for groups to adopt to facilitate their knowledge building in that domain. For example, just as (Stahl, 2013) identified dependency as fundamental for geometric thinking, (Roschelle, 1992) identified acceleration as fundamental for physics, and analyzed student discourse for signs of adoption of group practices associated with this concept. Then carefully sequenced and articulated topics could be presented for collaborative exploration, with guidance to stimulate productive interaction and knowledge-building discourse.

This could be coordinated with related course materials and instructional approaches, and accompanied by support for teachers to adapt and orchestrate the various resources. Researchers would need to collaborate with teachers over extended periods, as adoption of the CSCL intervention spread gradually and systematically through school systems. Given new educational networking platforms like MOOCs, collaborative curricula could be made available to students globally to learn together. This could both establish personal international cooperation among students and share curricular resources among developed and developing nations.

Such an envisioned scaling up of CSCL would require significant long-term commitment from government agencies to finance the research, dissemination, training, evaluation and support—as began to take place in Singapore and Hong Kong. CSCL research labs involved in such efforts would need to pool expertise in domain knowledge, learning theory, educational practice, teacher training, discourse analysis, software design, research expertise, grant management and other skills. Ideally, this would involve global networks of researchers. The Kaleidoscope funding during the late 1990s in the European Community might be considered the golden age of CSCL, where networks of researchers across Europe collaborated, resulting in some of the research reviewed above. Now a broader worldwide initiative is required, eventually including an emphasis on dissemination in school systems.

Advancing the CSCL vision is now feasible. CSCL theory can be refined and integrated to provide a unified conceptual framework for understanding collaborative learning as distinctive and as foundational. CSCL methodology can incorporate the sequential analysis of adoption of group practices. CSCL curriculum can be extended to meet worldwide needs. CSCL can play a distinctive role in evolving humanity to meet the challenges of the 21st century.

Significant progress in CSCL, especially including propagation to regular classrooms, is not a task for an individual researcher or even a single lab. It requires too many advanced professional capabilities and too great a long-term commitment. The CSCL community cannot manage this on its own. However, if the CSCL field is not centrally involved in setting the agenda and designing the direction, then the power of the CSCL vision to advance human cognition is unlikely to bear fruition. If the vision of CSCL can be maintained and exert a broad impact, then the discourse of humanity might be able to evolve a more complex understanding of phenomena like ecological sustainability, world peace, economic equity, informed political involvement. That would profoundly advance the CSCL vision and benefit the world.

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8. The Theory of Group Cognition

Abstract. The digital age of computer support has transformed human cognition. Although thinking always had social origins in the small-group interaction of family units, tribes, work teams and friendships, cognition is now enmeshed in networks of social media, technological infrastructure, online knowledge sources, global production. Computer-supported collaborative learning (CSCL) stands at the crossroads of this historic transformation. CSCL research provides a laboratory for studying the nature of collective intelligence or group cognition. It explores how collaborative learning by small groups can become a foundational form of knowledge building—including for the individual group members and for the society in which the groups live. This introductory Investigation presents a paradigmatic CSCL setting and highlights the role of group practices as vehicles for collaborative learning. It addresses the dual questions of how intersubjectivity is possible and what the preconditions are for establishing, supporting and maintaining intersubjectivity—providing central pillars of a theory of group cognition and suggesting implications for educational practice. It then delves into the structure of collaborative discourse, analyzing data from exemplary CSCL sessions. The analysis of group interaction points to a multilayered structure, in which individual, small-group and cultural cognition are intertwined.

Keywords. CSCL theory, group practice, paradigm example, social practices, co-experienced world, intersubjectivity, discourse structure, multi-layered analysis.

A Theory of Extended Cognition

The notion of group cognition proposes that human thinking and learning is at root interactional; the origin, influence and effect of human cognition extend essentially beyond the skull. We acquire our ability to think and to learn by adopting practices that arise within small-group interactions, such as in our family, work teams or collegial circles. Our thinking is responsive to and conditioned by our embeddedness in a physical, interpersonal and cultural environment—particularly the immediate discourse or action context. Our thought is oriented toward potential futures, which it opens for our interaction with others.

Group cognition theory poses an alternative to psychological theories of mental phenomena in individual minds as well as to sociological theories of societal structures existing independently of the people who inhabit those structures. According to group cognition theory, thinking and learning take place in the interactions among people and across the small groups of interacting individuals.

The theory of group cognition arose from study of student discourse in CSCL settings. It is aligned with the writings of Vygotsky, Lave, Bereiter, Koschmann, Engeström and Hutchins as well as with socio-cultural, distributed-cognition and embodied-cognition approaches generally. However, it maintains a systematic focus on the small-group unit of analysis, which others often lose to a psychological or sociological priority for the individual or society. It is also in keeping with 21st century post-cognitive philosophy, such as that of Marx, Heidegger and Wittgenstein—who critique mentalism and individualism.

Theoretical Investigations of Group Cognition

The theory emerged in the writing of *Group Cognition* (Stahl, 2006, MIT Press). Aspects of the VMT research project and technology were developed and described in *Studying Virtual Math Teams* (Stahl, 2009, Springer). Various perspectives on the research were extended and explicated in *Translating Euclid* (Stahl, 2013, Morgan & Claypool). A detailed longitudinal study of a team of students engaged in successful collaborative learning of dynamic geometry was analyzed and presented in *Constructing Dynamic Triangles Together* (Stahl, 2016, Cambridge). The theory of group cognition has important consequences for the methodology of the learning sciences and for educational practice, as well as for CSCL technology design and design-based educational research.

The implications of these studies of the VMT Project (2002-2016) for the theory of group cognition are taken up in the Investigations of Part III of this volume. Investigation 2 presents an introduction and overview of those essays, which represent my most important recent theoretical reflections on group cognition:

Investigation 15. *A Paradigmatic Unit of Analysis*. A specific example of CSCL research is presented as a useful prototype for thinking about the field of CSCL: the Virtual Math Teams (VMT) Project. It was designed to develop a technology platform and pedagogy for sustaining collaborative learning within small groups of students discussing mathematics and solving problems together. The VMT online environment was instrumented to collect data of student interactions. Using this example, it is argued that CSCL can offer a distinctive and timely new vision of educational research, focused on the small-group unit of analysis.

Investigation 16. *Group Practices.* Using multiple examples from VMT sessions, it is suggested that the adoption of shared practices by student teams is central to the collaborative learning that takes place in these groups. Group practices may or may not be derived from or related to either individual or cultural practices (such as rules from school mathematics), but they are adopted by the group in its collaborative work. Effective curriculum can be designed to encourage adoption of strategic group practices that contribute to skilled behavior in the contemporary world. Collaborative learning can be defined, designed, supported, fostered and evaluated in terms of the adoption of specific relevant sets of group practices.

Investigation 17. *Co-experiencing a Shared World.* CSCL raises the question of how multiple individuals can "share" practices, learning or thinking as proposed by the concept of group cognition. In this Investigation, examples of discourse data from several VMT sessions show how the members of an effective group participate together within a shared world. This experience of interacting within a co-experienced world provides a basis for their shared understanding. There are many ways that group members negotiate and sustain joint attention to objects, experience them together, negotiate their shared understanding and repair potential misunderstandings.

Investigation 18. *From Intersubjectivity to Group Cognition.* The question of how people can share understandings and understand each other is a philosophical issue. It has been discussed by a series of philosophers and social scientists. This Investigation tracks an evolving analysis of this discussion through about a dozen stages, culminating in the theory of group cognition.

Investigation 19. *The Constitution of Group Cognition.* The analysis of three VMT examples of interaction shows typical mechanisms used to achieve intersubjectivity. In particular, groups engage in extended sequences of dialogical responses to each other, building longer argumentation structures, such as informal derivations of mathematical conclusions. They remain involved in persistent co-attention to shared objects of interest. By co-experiencing these micro-worlds, they establish and maintain shared understanding.

Investigation 20. *Theories of Shared Understanding.* The usual view on how shared understanding among multiple minds is possible involves the notion of "common ground." This Investigation considers several prevalent, competing theories, including that of common ground. They are subjected to analysis in terms of evidence of how small online groups of students develop, check and maintain shared understanding, thereby constituting group cognition.

Investigation 21. *Academically Productive Interaction.* The recent pedagogical theory of "academically productive discourse" or "accountable talk" is primarily oriented toward individual cognition. Accordingly, it adopts the approach of cognitive convergence, guiding individual students to converge their own understandings with the understandings of other students, the teacher or the community. In the alternative paradigm of group cognition, one tries to guide groups of students to maintain and build on their co-presence and intersubjective, shared understanding to articulate their largely tacit shared group understanding.

Investigation 22. *Supporting Group Cognition with a Cognitive Tool.* CSCL is motivated by the potential to design technologies to support collaborative learning. In this Investigation, the use of a pointing tool in the VMT environment is explored. The tool permits a student to point with a graphical connecting line from a current chat-text posting to a previous post or to an object or area on the shared whiteboard. This supports deixis, the ability to direct the attention of others to an object of interest. Pointing is a ubiquitous means for supporting joint attention; this tool provides an effective digital analog of physical pointing.

Investigation 23. *Sustaining Interaction in a CSCL Environment.* Interaction in groups takes place through sequences of actions, such as text-chat postings, spoken utterances, drawing movements or bodily gestures. These can often be analyzed in terms of pairs of actions, such as the posing of a question followed by the offering of an answer. Here, the question elicits an answer, setting the stage on which a respondent is encouraged to provide an answer. In turn, the answer confirms by its responsiveness that the preceeding action was taken as a question and completes the meaningful question/answer interaction. While a question encourages interaction to continue with an answer, the answer could end the interaction. To sustain interaction, such response pairs must themselves be combined in larger structures.

Investigation 24. *Viewing Learning and Thinking in Groups.* This Investigation proposes a systematic approach to revealing larger structures in CSCL settings. It provides a view of group interactions such as those analyzed in the VMT Project as hierarchically structured, with events (like VMT Spring Fests), composed of sessions, covering multiple themes, built out of sequences of discourse moves, consisting of adjacency pairs, linking utterances, including references. This hierarchy provides a framework for analyzing student interaction with a view toward structurally understanding group cognition.

Investigation 25. *Structuring Problem Solving.* An extended interaction in VMT is here analyzed in some detail to show how a sequence of discourse moves is built up out of adjacency pairs, eventually carrying out a mathematical derivation by a small group. It is common to consider mathematical derivation the work of an individual thinker; however, here we see a group construct a result that no one of the individual students involved would have been able to do. The analysis of the derivation must be conducted at the unit of analysis of the group interaction.

This set of studies raises several central problematics of a theory of group cognition. These are particularly germane to CSCL, which focuses on small groups of students communicating over networked computers. The theory of group cognition claims that "groups can think." This is a new idea, reflecting that our era of digital technology has changed the nature of knowing, understanding, thinking. Now there can be various collective levels of interacting groups, networks or communities who interact across computer-based media. For researchers, the collective basis of cognition raises many issues, necessitating a rethinking of how to generate, collect and analyze data for studying collaborative learning and group cognition. The following aspects of these issues will be discussed in the remainder of this Investigation:

The nature of intersubjectivity, including the conditions necessary to establish and maintain it. Investigations 15, 16 and 17 take different approaches to conceptualizing the collective group and understanding the ways intersubjectivity can be established within the groups. See "Conceptualizing the Intersubjective Group" below.

A methodology for studying and understanding intersubjectivity. Investigations 18 and 19 trace theories of intersubjectivity and common ground. A key to the analysis of intersubjectivity is derived from ethnomethodologically informed conversation analysis, which developed the analysis of adjacency pairs in discourse. The theory of group cognition draws upon this for its analysis of the response structure of group interaction. See the section "Ethnomethodologically Informed" below.

The relationship of group cognition to artifacts, including tools to support collaboration. Investigations 20, 21 and 22 consider ways to foster collaborative learning through pedagogical and technological systems of support. This is critical for effective CSCL learning, which is necessarily mediated by technological artifacts (e.g., communication media and/or subject-domain representations). We need to consider how such mediation takes place. See "Artifacts and Collective Minds" below.

The interrelationships among multiple levels of description, such as individual, small group and community. Investigations 23, 24 and 25 are concerned with the structure of interaction at the small-group unit of analysis. It is important to consider this within the larger context of the relation of the small-group level to the individual and social layers of thinking and learning. See "Traversing Planes of Learning" below.

These thematic areas are discussed here based on editorial introductions to issues of *ijCSCL* that emphasized these areas (Stahl 2012a; 2012b; 2012c; 2013; 2015) and some of the papers published in those journal issues.

These editorials and papers are reviewed here to motivate reading the Investigations of Part III, which delve into these themes in greater depth and build on them as foundations of the theory of CSCL. They also serve to point to relevant discussions published in *ijCSCL* that were not able to be reprinted in full in this volume. They indicate the wealth of theoretical considerations in the back issues of the journal that could contribute to elaborating the vision of CSCL sketched in Investigation 1 and the theory outlined in this Investigation.

This set of themes defines central questions for a theory of CSCL, conceived as an attempt to understand and support learning at the small-group unit of analysis. They provide an understanding of intersubjectivity and of the group level of description in relation to non-human artifacts, individual subjects and encompassing communities or cultures. This Investigation thereby clarifies the conceptual background for the theory of group cognition elaborated in the Investigations of Part III.

Conceptualizing the Intersubjective Group

Intersubjectivity may be considered the defining characteristic of CSCL [Investigation 15] because it is what makes collaboration possible. *Intersubjectivity* is a concept that indicates *shared understanding* among people [Investigation 18]. This "sharing" is not a matter of individuals having similar understandings, but of them participating productively in a joint meaning-making discourse within a communal world.

Collaborative learning cannot take place if group participants do not have a shared understanding of what they are talking about or working on. On the other hand, "cooperative learning" can take place because this approach that was popular prior to CSCL involved individuals dividing up learning goals into small tasks that group members could accomplish individually, without extensive shared understanding and without engaging in processes of intersubjective meaning making. Many groups and team members opt for cooperation rather than collaboration because it is easier in that it does not require the establishment and maintenance of extensive intersubjectivity. However, it also lacks the power of collaboration to build knowledge across individual understandings. In cooperation, thinking takes place primarily in individual minds; the conclusions may subsequently be collected by the group. In such cases, the meaning of conclusions is relative to the individual understandings of the group members, and may or may not be similar for different participants. Cooperation typically lacks the thinking together that involves intersubjective meaning making and results in shared knowledge resulting from joint activity.

Many experimental interventions and published analyses of learning involving groups of students lack the focus on intersubjectivity, but still use the term CSCL. They may in fact be studying cooperative learning or even individual learning. In this volume, CSCL refers to learning that takes place at the group level of interaction and intersubjectivity. Unfortunately, such learning is relatively rare, even in the field of CSCL.

A group has achieved intersubjectivity if the members of the group interact well enough to pursue the group's aims together. Intersubjectivity must be built up gradually through interaction and be repaired frequently. CSCL research should explore the conditions and processes that are conducive to the establishment and maintenance of intersubjectivity among groups of learners. CSCL pedagogies should be structured to promote the intersubjectively shared understanding that makes collaborative learning possible. CSCL technologies should be designed to support intersubjectivity by providing media of communication and scaffolds for meaning making within specific domains of learning.

When CSCL theories discuss "groups," they are not referring to arbitrary gatherings of multiple learners, but to functional groups that have achieved a degree of intersubjectivity. The concept of collaborative learning in CSCL does not refer to a sum of individual learning that takes place among a group's members, but to the increase in inter-subjective understanding or collaborative knowledge building within the group that results from joint meaning making in a shared context. It involves the understanding expressed in the group discourse and the knowledge encapsulated in group products, such as texts or artifacts produced by the group. The group's understanding may differ from what any individual member might say, write or think when not interacting within the group.

This focus on the intersubjective group differentiates CSCL from other approaches to the study of human learning and educational instruction. It implies a research paradigm that prioritizes the group unit of analysis and studies groups that have achieved intersubjectivity. Analyzing an utterance (or chat posting) as part of a group interaction involves seeing how its meaning is constructed sequentially through its response to previous actions and elicitation of future behavior by other group members. The meaning of the utterance is inherent in the working of that utterance within the shared world of the group, not to be explained in terms of some purported individual mental thoughts accompanying the utterance. As in Ryle's (1968) thick description of a wink, the meaning of an utterance (or wink) is expressed by the utterance (wink) itself as an interactional action, not by assumed additional mental intentions of the speaker (winker).

Despite the centrality of the notion of intersubjectivity to CSCL, this concept has not often been explicitly discussed in the CSCL literature. Newcomers to CSCL therefore have difficulty determining the boundaries of the field. They may assume that CSCL is the same as traditional educational psychology or instructional design, except that it involves small groups and online technology. However, the importance of analyzing intersubjectivity at the group unit of analysis has become increasingly clear to many established CSCL practitioners. For instance, the *ijCSCL* Mission Statement specifies that the journal "features empirically grounded studies and descriptive analyses of interaction in groups, which investigate the emergence, development and use of practices, processes and mechanisms of collaborative learning." The central research questions are no longer what experimental conditions produce the most valued learning experiences or outcomes at the individual unit, but how intersubjective meaning making and understanding is established, maintained and increased within the *interaction in groups*, by social practices, small-group processes and interactional mechanisms analyzed at the group unit.

The shift of research from assessing individual student outcomes to analyzing group-level phenomena has been slow in coming and is still difficult to implement consistently. In the cooperative learning of the late 1900s, educational researchers like Johnson and Johnson (1999) or Slavin (1980) explored the effects of group interaction on learning outcomes of individual students. The focus was on individual cognition, but in cases where the individual was somehow influenced by being in a group. With the advent of CSCL, interest changed to the group processes that could be supported with networked-computer technologies. In their report on the evolution of research on the new approach of *collaborative* learning, Dillenbourg, Baker, Blaye and O'Malley (1996) noted that new methods were now necessary to study group phenomena. Although Koschmann (1996) proposed that this involved a paradigm shift, it has not been widely recognized what a radical change in perspective and methodology this shift to the group level implied.

Subsequently, Koschmann (2002) defined CSCL in terms of "joint meaning making." The centrality of intersubjective meaning making to the concerns of CSCL as a research field have been stressed programmatically in scattered proposals and examples, for instance in Investigations 4, 5, 12. Multiple attempts to define new methods corresponding to this agenda of group-level analysis were also proposed, as in Investigations 6, 7, 8, 9, 10 and 11 as well as several other *ijCSCL* articles.

After 20 years, CSCL researchers are just beginning to work out group-level conceptualizations, such as group cognition, group knowledge construction, group agency, group engagement, group metacognition, group practices and so on. Some researchers now see CSCL as pursuing a post-cognitive paradigm distinguished from the cognitivism of traditional learning sciences based on cognitive psychology [Investigation 15].

Co-Operative Action

Intersubjectivity goes by many names. Goodwin (2013; 2018) has recently developed an analysis of the essential intersubjectivity of human cognition within a post-cognitive perspective, grounded in a number of ethnomethodologically informed analyses of interactional data, including family members conversing, children playing and arguing, anthropologists or chemists learning analytic skills and videotaped evidence being presented in a courtroom. As diverse as these settings are, they all involve small groups of people in face-to-face interaction. In this volume, we will adopt much of Goodwin's perspective, but apply it within computer-mediated scenarios.

Like group-cognitive theory, Goodwin's post-cognitive approach is not focused on psychological states as making human cooperation possible, but rather on "public social practices that human beings pervasively use to construct in concert with each other the actions that make possible, and sustain, their activities and communities" (2018, p.7). In place of a model of the speaker that takes as its point of focus mental phenomena within the individual actor, Goodwin identifies how people constitute their participation in discourse through their ability to "engage in appropriate but differentiated ways in a field of interactively sustained action constituted through the public organization of language use" (2013, p.15). These ways correspond to what Investigation 16 calls group practices.

The accumulation of group practices is central to the organization and evolution of human culture, collective knowledge and social life (Investigations 7, 16); the adoption and use of these practices by small groups pervades social life. Goodman, citing the philosopher and semiotician Pierce, highlights in particular the central importance of diagrammatic reasoning in human thought, noting that geometry provides a perspicuous example. The historic role of Euclidean geometry as a training ground for cognitive practices which integrate visual, logical, gestural and representational practices was a motivation for the VMT Project's focus on collaborative dynamic geometry as a subject domain.

Goodman provides an analysis of co-operative action that can usefully be applied to the study of VMT interaction data. He chose the term "co-operative" because people typically perform specific operations in coordination with each other. For instance, a speaker may decompose materials provided by a previous speaker and then reuse them with transformations. Goodman takes this process of decomposition and reuse of resources to be a very general and unique characteristic of human cognition. Mankind innovates by analyzing (taking apart) ideas and tools accessible in the social world and synthesizing (recombining) them in transformed ways. In particular, our speech is generated by decomposing and reusing with transformation the resources made available by the preceding speech of others. So, their language becomes ours, and ours is a form of theirs: "We inhabit each other's actions" (Goodman, 2018, p.1).

The operations of decomposition and transformation take place in multi-dimensional settings, resulting in what Goodman calls environmentally coupled gestures. These require for their understanding not only a gesturing hand, but also the environment being pointed at and co-occurring language that formulates what is to be seen there in a specific way. For instance, anthropologists train their students to see and discuss subtle shades of ground at an excavation by pointing to color charts and using technical terminology. Similarly, students in VMT learn to construct challenging geometric dependencies by highlighting or making salient specific graphical elements on the computer screen and chatting about them using geometric terminology. This kind of co-operative action or group cognition is a fundamental way in which groups accumulate group practices, group members become more skilled, and the community builds knowledge. As Goodman puts it,

> The accumulation and differentiation through time within local co-operative transformation zones of dense substrates create a multiplicity of settings for action. Each of these must be inhabited by competent members who have mastered the culturally specific practices required to perform the activities that animate the lifeworld of a particular community. Through the progressive development of, and apprenticeship within, diverse epistemic ecologies, communities invest their members with the resources required to understand each other in just the ways that make possible the accomplishment of ongoing, situated action. (2013, p.21)

Not only does this process make possible new professions and realms of knowledge, but it also recursively forms the basis of intersubjectivity, required for all mutual understanding.

Translating Goodman's view of co-operative action to the concrete situation of the VMT paradigmatic case of CSCL, we can observe student teams decomposing and transforming each other's contributions. Trausan-Matu (Trausan-Matu, Dascalu & Rebedea, 2014; Trausan-Matu & Rebedea, 2009) has analyzed VMT transcripts using Bakhtin's notion of polyphony, showing how students build on each other's word use to inhabit an inextricably interwoven shared world.

Perhaps even more striking would be an analysis of how a team working on geometry decomposes and transforms each other's construction efforts. Interaction in VMT includes graphical (geometric construction) actions as well as linguistic (chat postings). Although it would be tricky to present a detailed study of this concisely, the construction data is now available in the recordings of the Cereal Team in their Winter Fest 2013 interaction, especially Session 6 (Stahl, 2015). Here, the three students took turns extensively exploring how to construct points, lines, circles, triangles, squares and polygons with specific dependencies. There was lots of trial and error, but an adequate analysis would show that it was by no means random efforts. Each student closely observed the deadends that the others ran into. They decomposed the false starts by erasing the shared workspace and then reconstructing the effort with key transformations, which eventually led to success. The successes were immediately recognized by the whole group and adopted into the future work of the group and of its members. This resulted in a shared understanding of their intersubjective meaning making in the shared VMT world.

The Conditions of the Possibility of Intersubjectivity

Several articles in the 2015 *10*(3) issue of *ijCSCL* focused on intersubjectivity; they illustrate and further develop a group-level focus of CSCL research. For instance, the first article provides a discussion of Habermas' philosophy as it relates to CSCL issues and introduces to the CSCL audience the work of the contemporary author who has written the most on the concept of *intersubjectivity*. Then, three papers analyze the intersubjectivity of small groups of students in different ways. One looks at how *groups learn how to learn together* with support from specific CSCL tools. A second transforms the concept of engagement to the group unit of analysis as collaborative *group engagement*. The final one makes a parallel move for *formative feedback and metadiscourse*, applying them at the group level. Together, they offer stimulating glimpses of CSCL theory, technology, meta-learning and analysis focused on the group as agent.

In his introduction of Habermas' philosophy of communicative action to the CSCL community, Hammond (2015) translates from Habermas' application of this theory in the public sphere of traditional media to the online world of CSCL. For Hammond, Habermas is relevant because he brings a fresh, well-considered and critical perspective to the discussion of joint knowledge building. In particular, Habermas' writings provide a framework for judging the evidence we bring to the analysis of collaborative learning as well as for valuing the evidence that our student subjects provide in their argumentation. Habermas defines the conditions necessary for the establishment of intersubjectivity, such as the inherent assumption of an ideal speech situation underlying communicative action. What Kant's *Critique of Pure Reason* did for the individual mind, articulating the conditions of the possibility of human knowledge, Habermas translated to the group level, explicating fundamental discourse conditions necessary for intersubjective meaning making in social collectivities.

Consider a student chat, a discussion forum or a medium like Wikipedia. How should we judge the quality of the knowledge building that takes place there? Moreover, how should one judge the quality of researchers' analysis of that knowledge building? Habermas provides a standard for judgment that is grounded in the nature of human discourse. He argues that effective communication would be impossible without the underlying postulation of an ideal speech situation—even if this ideal is never in fact fully achievable (Habermas, 1981/1984). The act of communicating with the aim of establishing intersubjectivity, making shared meaning and building knowledge together assumes that there is no other force of persuasion at work than that of the better argument and no other motivation than the cooperative search for truth. Enlightened discourse is only possible under the assumption of this goal. Of course, there always are other forces and motivations present. But the character of the ideal speech situation that underlies collaborative dialog provides a basis for critiquing those systematically distorting forces. For instance, if knowledge building assumes that no one can impose his or her views through force rather than through supported reasoning, then appeals to authority or intimidation can be soundly censured.

Habermas' theory is, additionally, more complex and nuanced. A major contribution of his work was to distinguish realms with different criteria within the public sphere (Habermas, 1967/1971). There is, as Hammond puts it, the objective world (of nature and labor), the social world (of institutions and interaction) and the subjective world (of personal experience). Each has very different criteria of validity. The objective world follows the laws of physics and involves human mastery over nature through technical, goal-oriented, instrumental calculation; the social world, in contrast, involves normative rules reached through negotiation; while the subjective world is a matter of one's self-narrative.

Consider the research task of analyzing an online team of students collaborating on a geometry construction. Certainly, this involves comparing the team's work with mathematical knowledge developed in the axiomatic world of mathematical relationships. However, it also involves tracking the development of the team's adoption and mastery of its own group practices of collaborating and of working on geometry in the team's intersubjective world. Furthermore, it may be possible to assess individual learning by team members as a personal-world spin-off of their teamwork. Each of these dimensions has quite different methodological criteria. Seeing how each is accomplished with the mediation of specific CSCL pedagogical approaches or CSCL technological tools can feed into design-based research for improving support for collaborative knowledge building.

Habermas' distinction between the objective, social and subjective realms gives him leverage for his critiques of modernism and other popular philosophies, extending the critical social theory of the Frankfurt School. As cited by Hammond, Habermas' concern with mutual recognition led him to criticize classical liberalism for reducing ethical liberty to a "possessive-individualist reading of subjective rights, misunderstood in instrumentalist terms." There are many analogous examples in the CSCL literature, where social phenomena are inappropriately reduced either to individual subjective criteria or to instrumental objective criteria. Hammond suggests that a focus on intersubjectivity could provide a corrective in such cases and open up new perspectives for design and research. It is important to distinguish different levels of analysis carefully and to apply the appropriate evaluative criteria or analytic methods to each.

Intersubjective Learning to Learn

As a foundation of all communication and cognition, intersubjectivity applies to education specifically. Teaching students to learn how to learn or to develop "thinking skills" has long been considered important—particularly in the information age, where knowledge evolves rapidly (e.g., Investigation 13; Wegerif, 2006). In their research report in the same *10*(2) *ijCSCL* issue, Schwarz, de Groot, Mavrikis and Dragon (2015) extend this goal to the group level with their construct of learning-to-learn-together. A core component of this approach is supporting groups of students to engage in argumentation as a form of intersubjective meaning making. Schwarz and colleagues situate computer support for argumentation in an innovative dual-interaction space.

The authors take an iterative design approach to developing a software environment, curricular tasks and teacher roles for supporting learning-to-learn-together. They hypothesize that mutual engagement, collective reflection and peer assessment may be three critical group processes to encourage and to investigate. To explore these, they design a prototype with two primary components: a construction space and an argumentation space. The construction space includes a selection of domain-specific modeling applications to support student inquiry in specific topics of mathematics or science. This provides a mutually visible "joint problem space" for collective reflection by the group on the progress of its inquiry. The software creates a shared world for mutual engagement, as opposed to individuals trying to solve a challenging problem on their own. As one group member performs an action in the space, the others assess that action in the argumentation space, either affirming it or questioning it. This prompts the students to build on each other's actions, producing a joint accomplishment.

In some dual-interaction systems, like VMT, a text-chat feature accompanies an online construction space. This provides the possibility of engaged discourse, group reflection and peer assessment when group members are not situated face-to-face. However, the described argumentation system goes beyond this with a sophisticated planning/reflection tool. Even if the students are sitting together around a shared computer, this tool prompts, guides and supports team efforts at planning steps for the group to take (collective agency) and it facilitates team reflection on the current state (collective responsibility).

While the software mainly displays advice and ideas from the teacher or from individual students, its persistent visibility and its manipulable structure allow it to influence group agency and meta-learning. The potential power of this approach seems to come from the integration of the support for argumentation and reflection by the group with the inquiry activity itself in the shared inquiry environment. As always in CSCL, success also depends on a culture of collaboration: appropriate motivations/rewards, careful training in collaboration and subtle mentoring. The emphasis of the pedagogy and the support throughout is on the group as meta-learner. Group learning here is a form of intersubjective meaning making, incorporating group agency and group responsibility.

Intersubjective Engagement

In the next presentation of the *10*(2) issue, Sinha, Rogat, Adams-Wiggins and Hmelo-Silver (2015) provide a multi-faceted conceptualization and operationalization of intersubjectivity based on aspects of what they term "group engagement." Using this approach, they provide a clear illustration of a team of students that does not form an intersubjective group contrasted by one that does. The construct of group engagement developed in this paper allows the authors to identify this contrast and to analyze it using both quantitative and qualitative methods. The quantitative approach includes statistical correlations based on ratings of several aspects of group engagement, measured in five-minute intervals. The qualitative approach involves thick descriptions of illustrative excerpts of group discourse. The descriptions relate the interactions within the groups to their work (or lack thereof) of meaning making in establishing the engagement of the group as a whole in its problem-solving task.

A major achievement of the paper is to shift the analysis of engagement—which is increasingly popular in CSCL—from the psychological individual to the intersubjective group unit of analysis. The authors are explicit about this. Their observational protocol is designed to situate engagement within the collaborative group, its joint problem and its shared situation. For instance, the dimension of social engagement reflects group cohesion, or evidence that the task is conceptualized as a team effort, rather than as an individual activity. The contrast of one group's use of the subject "we" versus the other's use of "I" reflects in the details of the discourse the distinction documented in the ratings—showing that the distinction is actually one made by the group.

The paper is an impressive response to the cited prior research on engagement. According to the literature review, earlier studies generally operationalized engagement as consisting of a single dimension, as a stable state and as a characteristic of the individual learner. In addition, the cited work decontextualized engagement from concomitant conceptual and disciplinary tasks. By contrast, this study proposes a differentiated, evolving, multi-faceted and group-based model of engagement and applies this model to explore an insightful example from actual classroom practice. The paper's mixed-methods analysis reflects a careful attention to the unit of analysis, operationalizing engagement at the group level. Thereby, it adds in a rich way to our conceptualization of intersubjective meaning making.

Intersubjective Metadiscourse

Like the preceding paper, the one by Resendes et al. (2015) also uses mixed methods, with both quantitative and qualitative analysis. While collecting data at both the individual and group units of analysis, its focus is also at the group unit. In fact, it goes a step further than the previous paper and most other CSCL reports by capturing the outcomes at the group level. Here, because the main data source is a Knowledge Forum database, the group product of shared notes responding to each other within the group is the most important object for examination in response to the primary research question. Thereby, the correlation of the experimental condition with resultant collaborative learning or knowledge building can be conducted at the group level.

The social-network analysis of the Knowledge Forum data shows the effect of experimental feedback tools on the group process and the degree of intersubjectivity established by each group. The paper's analysis strikingly indicates that in the control condition most students are not strongly connected to other students, whereas in the experimental condition everyone is strongly connected to everyone else. Because the social-network connections here represent sharing of vocabulary terms—such as those displayed in the experimental condition's feedback tool—this means that there is a higher degree of intersubjective, shared understanding in the experimental groups. Shared understanding at the group unit of analysis is not dependent upon individuals' cognitive states, internal representations or personal understandings, but is visibly displayed in the team's unproblematic use of shared language.

We are shown further evidence of increased group metadiscourse through the analysis of group discussion in a number of propitious interaction excerpts. While these demonstrate the experimental group's comprehension of the visualizations of their group discourse (displays of its use of domain vocabulary and of Knowledge Forum epistemic markers), the primary metadiscourse moves (prompting the group to plan, question, analyze, explain) were made by the teacher, rather than by the student group. The experimental intervention at the group level led to productive metadiscourse, but this was not at all independent of the teacher. Thus, the study merely indicates a potential for the design of formative assessment visualizations that represent group-level behaviors and that support group metadiscourse. It does not demonstrate that the implemented tools led to metadiscourse by student groups on their own. The students may need more experience with this approach or more maturity to take on this form of agency by the student group. Nevertheless, the paper offers stimulating design suggestions: group-level formative feedback can represent group vocabulary; support the group to evaluate its own progress; give feedback on secondary processes (like vocabulary building, rather than directly on learning or task accomplishment); suggest positive steps (rather than just identify deficiencies); facilitate self-assessment by the group; and guide individual students to become more effective group members.

Together, the papers in issue *10*(3) of *ijCSCL* suggest the centrality of intersubjectivity to a theory of CSCL and provide inspiring examples of how to explore and articulate aspects of our conceptualization of group intersubjectivity.

Ethnomethodologically Informed

The research field of CSCL is ethnomethodologically informed, or at least ethnomethodologically influenced. This has not always been the case, although there is a logic to this growing tendency.

Ethnomethodology (EM) is an approach to conducting research in the human sciences founded by Harold Garfinkel and largely defined by his *Studies in Ethnomethodology* (Garfinkel, 1967; Garfinkel & Rawls, 2012). EM addresses the "methods" that members within a given linguistic community use to establish and maintain intersubjective understanding. Since CSCL can be characterized as being focused on joint meaning making, the analysis of prevalent meaning-making methods seems particularly relevant to the methodological quandaries of CSCL research.

Ethnomethodology has been slow to catch on in CSCL, in contrast to its role in allied fields like CSCW, where it seems to be a dominant research paradigm. There are a number of theoretical and historical reasons for this. For instance, as discussed below, practitioners of EM eschew research questions and theoretical framings because these could obscure the meaning-making perspective of the people whose interactions are under investigation. This injunction against guiding theory makes it difficult to integrate EM studies into the educational and design agendas of CSCL investigators. In addition, the case-study approach of EM to analyzing naturally occurring events is at odds with the traditional emphasis in educational and psychological research on controlled experiments and statistical generalizations. CSCW is based more in social sciences, in contrast to the psychology backgrounds of many CSCL researchers.

On the other hand, there are strong arguments for viewing the ethnomethodological approach as especially appropriate for analyzing computer-supported collaborative learning. In particular, a major stream of research within EM has been conversation analysis. This is the analysis of talk-in-interaction, as pioneered by Sacks (1965/1995) and other colleagues of Garfinkel. An early finding of conversation analysis was the system of turn taking in face-to-face informal conversation. While this system does not apply directly to such CSCL interactions as online text chat about an academic topic (Zemel & Çakir, 2009), the underlying techniques of sequential analysis (systematized by Schegloff, 2007) seem highly applicable to the analysis of meaning making in CSCL settings. Such sequential analysis explicates the evidence embodied in instances of discourse that reveal meaning-making processes taking place in small groups [Investigation 25]. It looks at the semantic, syntactic and pragmatic details of how utterances respond to each other and elicit new responses in the flow of group cognition.

The Historical Traditions of CSCL Research

Largely, early CSCL investigators turned from inspirations in computer science and artificial intelligence to the fields of educational psychology and sociology to find methods of studying the effects of using CSCL systems in classrooms or in laboratories. The theories and research paradigms that they brought in from these established fields focused on either the individual student or the larger society as the unit of analysis. Educational theory operationalizes learning as a hidden change in mental state of student knowledge from before an intervention to after, as measured indirectly by pre- and post-tests of individual students. At the other extreme, social science approaches hypothesized societal forces that could not be observed directly, but could be inferred and measured by controlled experiments using statistically significant numbers of randomly selected subjects.

Ethnomethodology—drawing on philosophical influences from phenomenology and reacting against functionalist approaches to sociology—takes a different tack, centered on what is made visible in the interactions between people. EM argues that one can observe the meaning-making processes at work by carefully studying the discourse between people; one does not have to make inferences about hidden changes in mental models or invisible social structures. Furthermore, EM studies can focus on the small-group unit of analysis, which seems most appropriate to analyzing collaborative learning. While other areas of education and of sociology may seem centrally concerned with individual or societal units of analysis and while collaborative learning may also involve processes and phenomena at those levels, the meaning making in contexts of joint activity which is definitive of CSCL takes place primarily at the small-group level, even if a complete understanding will ultimately need to tie all the levels together.

The ability to conduct microanalysis of interaction was historically made possible by recording technologies, which allowed utterances to be replayed and slowed down. Conversation analysis arose in the age of the tape recorder. That technology made it possible to hear exactly what was said and how it was articulated. It allowed the production of detailed transcripts, which represent intonation, pauses, emphasis, restarts and overlaps so that the mechanisms of verbal interaction could be studied. Subsequent development of video recording led to analysis of gesture, facial expression, gaze and bodily posture as important but generally unnoticed aspects of interpersonal interaction. For online communication typical of CSCL, computer logs and even the ability to replay synchronous interaction can provide adequate data sources necessary for the study of how students actually engage in computer-supported collaborative learning.

Applied to CSCL, the approach of EM implies that we can observe and report on the ability of given technologies and pedagogies to mediate collaborative interactions between students in concrete case studies. EM suggests ways to do this systematically, with intersubjective validity, and to generalize the findings. Insights from this can be used to critique the designs of interventions and to suggest redesign criteria. To make these claims about EM plausible, we will need to review some of the principles of EM.

The Theoretical Framing of CSCL Research

There is a prevailing notion that EM is atheoretical or even anti-theoretical, that it rejects all theorizing. Yet Garfinkel and Sacks (1970) were highly theoretical thinkers, influenced by philosophy, sociology and communication theory. In fact, EM represents a strong theoretical position about the nature of human reality and the possibilities of comprehending it. EM claims that human social behavior is structured by a large catalog of "member methods"—patterned ways of making intersubjective sense with other members of one's linguistic community. Furthermore, these member methods are "accountable" in the sense that they provide an observable account of their own character. People's actions are designed so that the meaning of the actions will be recognizable by others within the given discourse situation. This accountability is necessary for intersubjective understanding among members. But it has the secondary consequence that researchers can understand the methods as well (given certain conditions). The theory of EM thereby explains how EM is possible as a scientific enterprise.

The member methods of a linguistic community contribute significantly to the social order of activities within the community. The social structure is enacted in the very interactions of the members by virtue of their use of these methods; the accountability of the methods, as they are realized, reveals to the other participants (and potentially to researchers) evidence of what is being enacted. As Garfinkel put it, "any social setting [should] be viewed as self-organizing with respect to the intelligible character of its own appearances as either representations of or as evidences-of-a-social-order" (Garfinkel, 1967, p. 33). There is reflexivity at work between the meaning of an elemental interaction (e.g., an utterance/response pair) and the local context of the on-going discourse, in which the utterances are situated within a context whose significance they interpret in a continuously emergent way. The theory of EM is formulated in its concepts of member methods, accountability, reflexivity, etc.

The reason that EM is often considered to be atheoretical is that it systematically rejects the kind of theoretical framing that is associated with many other research approaches. For instance, in other paradigms an experiment and its analysis are motivated and structured by a theory or conceptualization of the phenomena to be studied. There may be a specific research question that the researchers have in mind. There may even be hypotheses about how the experiment will turn out based on preconceptions. While scientific researchers must remain open to their hypotheses being disproven by the evidence, the posing of research questions and hypotheses define a research perspective within which the evidence is pre-interpreted. For instance, CSCL discourse data might be coded according to a set of codes designed to make distinctions relevant to this perspective, experimental conditions will be structured to test these distinctions and coders will be trained to categorize their data from this perspective—all before the students even interact or produce their utterances.

EM, in explicit contrast, wants to understand the data from the perspective of the participants in the study (e.g., students). Because the analysis of discourse is a human science, it must take into account what the discourse means for the speakers and audience. The participants are viewed as people engaged in meaning making, and EM researchers want to understand the meaning that the participants are making. EM researchers do not want to impose a perspective on the data analysis that is based on their own preconceived theories about the interaction. Rather, they want to engage in "thick description" (Ryle, 1949) of the discourse to explicate the meaning making that is taking place in the discourse and that is displayed in the accountability of how it is formulated. The fact that the discourse is accountably intersubjectively understandable allows the researcher to analyze the meaning that is implicit in the discourse as it sequentially unfolds.

This is the sense in which EM rejects theory: that it adopts the participant perspective on understanding the meaning in the data, rather than imposing a perspective based on a theoretical research framing. There has been considerable debate within CSCW about how EM analysis can be used to guide design of collaboration systems if it cannot be directed toward theoretical issues (e.g., see Crabtree, 2003). But the stricture against theory in EM is only against imposing an *a priori* analysis framework, not against drawing theoretical consequences from case studies. So, one can, for instance, study the discourse of students embedded in a computer-supported interaction, and analyze the nature of the methods they use—which they enact, adapt or create—for achieving their collaborative tasks. The details of these methods can have design implications, such as addressing technical barriers that resulted in unnecessarily cumbersome behaviors. Thus, EM can contribute to the analysis phase of design-based research (DBR Collective, 2003), which is a widespread approach in CSCL to the design of effective collaboration technologies.

The Ubiquity of Methods

Ethnomethodology posits the existence of member methods pervading all of social life. EM research for the past fifty years has documented many such methods, for instance in informal conversation, in doctor-patient discussion, in mathematical proof, in criminal interviewing and in workplace communication. These methods are often sedimented in the traditional design of the tools we use and in the clichéd turns of speech within our vernacular. They constitute our myriad overlapping cultures.

Sacks (1965/1995) argued that the pervasiveness of member methods meant that one could profitably study almost any interaction and learn from it about the nature of social existence. He argued that the universal application of these methods was necessary if people were to understand each other. In the CSCL literature, one often talks about the establishment and maintenance of "common ground" (Clark & Brennan, 1991) as providing the foundation for intersubjective understanding. However, according to EM, it is not a matter of the participants having corresponding mental models of propositional knowledge; rather, intersubjectivity is founded on co-experiencing a world through using shared methods of communication [Investigation 17]. These methods provide "resources" for engaging in specific domains of the social world. According to the EM viewpoint, collaborative learning does not consist in the storing of propositional knowledge as mental contents in individual minds, but in the increasing ability to enact relevant resources or shared practices in interactions with others.

By looking carefully at interactions in CSCL settings, we can analyze the methods being applied. Because the acceptance of these methods is widespread within a culture, the results of a single case study can have quite general ramifications. Of course, to accept the implications of a single case study—or even a small catalog of case studies analyzing variations on a method—as valid and of general applicability, we need to ensure lack of bias or idiosyncrasy. This is usually addressed in EM by "data sessions" and other mechanisms to involve multiple analysts (Jordan & Henderson, 1995). If discourse under analysis displays an account of itself, then a group of experienced analysts who share the relevant cultural understanding with the discourse participants should be able to reach a consensus about the meaning being created in the discourse. EM case-study publications frequently include very detailed transcripts of the relevant discourse excerpts to enable readers to confirm the analysis based on their own cultural understanding.

Group Practices

The identification of group practices—their adoption and use by groups—seems central to analyzing intersubjective meaning making and collaborative knowledge building in CSCL. Investigation 16 delineates a theory of group practices and proposes that CSCL methodology be centered on this.

Group practices are routinized behaviors that a group adopts and that ground intersubjectivity by providing shared understanding. They may mirror established social practices or EM-style member methods, such as procedures commonly used by experts in their work but as yet unknown to the students. The theory argues that the analysis of group practices can make visible the work of novices learning how to inquire in science, mathematics and other fields. These ubiquitous social practices are invisibly taken for granted by adults in their professional lives, but can be observed as they are brought into usage, and rigorously studied in adequate traces of online collaborative learning.

The analysis of the enactment of group practices by teams in CSCL contexts can systematically inform the design, testing and refinement of collaborative-learning software, curriculum, pedagogy and theory. Applied to the evaluation of trials of CSCL innovations, the analysis of how student teams adopt or fail to adopt desirable group practices contrasts with traditional pre/post comparisons that miss sequential interactional processes or that reduce group phenomena to either individual or social factors. Investigation 16 concludes by proposing that CSCL can be re-conceptualized as the directed design of technology to foster the adoption of targeted group practices by student teams.

The theory of group practices emerged from a longitudinal case study of a team learning the basics of dynamic geometry in eight hour-long VMT sessions. This data provides the prototypical example for the vision of CSCL being offered in the present volume. The interdisciplinary VMT research team at the Math Forum conducted a year of weekly data sessions on this data, resulting in a book-length analysis of the collaborative learning that took place (Stahl, 2016). A daylong workshop on the data was also held involving international researchers, and findings were discussed during visits by the author to European research labs.

During eight hours of chat and manipulation of geometric representations, the group employed countless social practices, most of which were intuitive, tacit and non-problematic for the students. However, over sixty group practices were also identified in the analysis as practices that had to be explicitly negotiated and adopted through group interaction processes.

The catalog of these adopted group practices agrees well with lists of social practices enumerated in the research literature. For instance, it includes online analogues of group practices ("member methods") defined by face-to-face conversation analysis: sequential organization (response structure), turn taking, repair, opening and closing topics, indexicality, deixis, linguistic reference and recipient design. Other group practices correspond to practices CSCL has previously investigated as providing foundations for intersubjectivity: joint problem spaces, shared understanding, persistent co-attention, representational practices, longer sequences and questioning. As observed in various VMT studies, practices in mathematics education include: mathematical discourse and technical terminology; pivotal moments in problem solving; and the integration of visual/graphical reasoning, numeric/symbolic expression and deductive narrative. In addition, there were group practices that are necessary for constructing figures with specific dependencies in dynamic geometry.

It is likely that the VMT team picked up many group practices unproblematically, without having to go through an explicit negotiation process because the available resources—including the curriculum texts or classroom presentations before the online collaboration—guided smooth, tacit adoption of the practices. The curriculum, software environment and teacher guidance were based on careful study of what sorts of practices are involved in productive interaction related to collaborative dynamic geometry. This involved the researchers and the teachers developing personal experience with, for instance, constructing figures in Euclidean and dynamic geometry. They also read research reports about how students learn this domain. There are many physical practices involved in constructing different geometric elements on the computer screen and additional practices involved in dragging them to make sure they behave as desired. There are practices involving physical dexterity, computer manipulation, geometric relationships, communication, terminology, problem solving, explanation and so on. In a collaborative setting, these must often be shared as group practices.

The identification of group practices has substantial implications for the design and evaluation of CSCL software, curriculum, pedagogy and experimental intervention. According to the theory of instrumental genesis described in Investigations 6 and 7, it is not sufficient for a CSCL designer to have good ideas and honorable intentions; one must develop an initial prototype environment and try it out with groups of students. Based on observation of problems, the prototype must then be iteratively re-designed and refined. By observing breakdowns in group interaction and the gradual enactment of new group practices in response to the breakdowns, a designer can identify problem areas and constructive processes that need additional support. The analysis of group practices provides a systematic analytic method for driving CSCL design.

The analysis of adoption of group practices can be conducted either informally or rigorously. For instance, in browsing through the just completed online interaction of student groups one day, I noticed that one group had accomplished something impressive in their geometrical construction. However, they had not had time to reflect on what they had done in terms of negotiating new group practices or engaging in discourse about the "dependencies" that they had established in their construction. I had designed the tasks with the goal of deepening the students' understanding of mathematical dependencies, so I wanted the students to spend more time interacting around their accomplishment. I emailed the teacher and suggested that she extend her groups' work on this task the next day. Because I knew that I had designed the intervention with the intention of facilitating the adoption of group practices of discourse and construction related to the concept of dependency, I was oriented to scanning for this when replaying the student sessions. Informal analysis could drive design, altering the sequencing of topics and changing the wording for the next iteration of the course.

By contrast, to develop a deep understanding of what the student team accomplished in that session and how they built their knowledge interactively, I had to go over the data many times, in slow motion, and analyze it with other researchers experienced with mathematics learning. Eventually, we developed a nuanced sense of the development of the team's group cognition. We saw how its shared understanding of mathematical concepts like dependency had developed significantly, but was still not robust. We catalogued the repertoire of group practices the team now shared, which provided it with an initial fluency in collaborative dynamic geometry, as intended by the design of the eight-session curriculum. We could then document the longitudinal development of mathematical cognition at the group level and observe the articulation of that newly acquired understanding by the team members' discourse. We could specify the vaguely characterized cognitive evolution from concrete visual to abstract conceptual thinking in terms of the accumulation of adopted group practices, which we could observe and document.

Analysis of how the Cereal Team developed their mathematical understanding as a group illustrates the working of intersubjective meaning making through the interaction among team members. However, it is also important to take into account the role of artifacts, such as geometry constructions and labeled diagrams in this computer-supported collaborative learning.

Artifacts and Collective Minds

The age of simple objects like well-designed artifacts, minds confined inside of skulls and cultures cloistered in the tacit background has been left in the fading past according to current socio-cultural theory [Investigation 3]. We are now enmeshed in dialectical processes of social enactment, whereby designed objects continue to evolve well after they enter into the structuring of our thought patterns [Investigation 6].

Biological human evolution has long since transformed itself into cultural evolution, proceeding at an exponential pace [Investigation 7]. Along the way, thought overcame the limits of individual minds to expand with the power of discourses, inscriptions, digital memories, computational devices, technological infrastructures, computer-supported group cognition and virtual communities [Investigation 8]. Both human cognition and its mediation by technological artifacts morph from fixed nouns into process verbs [Investigation 10], like "cognizing mediating" (Stahl, 2012a)—where human cognition and technological media shape each other in ways we are just beginning to conceptualize.

The owl of Minerva flies only at night, according to Hegel's (1807/1967) metaphor: theory—which is one's time grasped in concepts—lags behind the continuous unfolding of practice. As today's viral software successes rapidly outstrip our design theories, we must try to understand the ways in which new generations of users adopt and adapt their digital tools, thereby defining and redefining their conceptual, social and pragmatic ties to their worlds. Hegel theorized the dialectic between subject and object, proposing that the identity of the human subject is formed when a subject subjects an object to goal-oriented design (Stahl, 2006, p. 333f), creating an artifact within the effort to forge intersubjectivity and its spin-off, the individual's self.

Vygotsky (1930/1978) recognized the role of double stimulation in mediated cognizing: that the subject's access to an object is mediated by tools such as hammers, names and physical-symbolic inscriptions, so that in higher-order human cognizing we are stimulated by both an intentional object and a cognizing-mediating tool. It is this mediation of cognition by artifacts and via other people that opens the zone of proximal development, allowing the individual mind to first exceed and then later extend its limits. Engeström's (1987) concept of expansive learning added the cultural dimensions from Marx' social theory to Vygotsky's simple triangle of subject-artifact-object. Henceforth, socio-technical understandings of artifacts have to situate them culturally, historically, politically.

We have considered the labyrinthine nature of the artifact's affordances previously within theories of human-computer interaction (Hutchins, 1999; Norman, 1991), cognitive science (Gibson, 1979; Hutchins, 1996) and CSCL [Investigations 3, 4, 5 and 11]. For instance, based on Merleau-Ponty's (1945) philosophy, Bonderup Dohn (2009) argued that the affordances of an artifact were potentials realized in response to human behaviors.

The 2012 *7*(2) issue of *ijCSCL* focused on the role of artifacts in CSCL. The issue opens with Investigation 6, which explores the nature of artifacts by comparing the theory of affordances with the theories of structuration and of instrumental genesis. Structuration (Giddens, 1984; Orlikowski, 2008) is a well-known theory developed to account for the dialectic between social structures and the local interactions, which are both constrained by these structures and reproduce them. Instrumental genesis is a recent theory developed in France by Pierre Rabardel and his colleagues. Investigation 6 introduces the theory of instrumental genesis to the CSCL community and explores how the theory might impact work in CSCL, at methodological, technological and theoretical levels.

Investigation 6 compares the three major recent theories about the interaction between artifacts and people, using a concrete case study of a typical CSCL setting. It argues in favor of the general approach of instrumental genesis as an analysis of the micro-genesis of artifacts and as the best available description of the nature of tools, particularly for CSCL. The theory of affordances tends to focus on the individual, for instance with Gibson's biological perspective, Norman's use of mental models, or Piaget's schemas in individual minds. In contrast, the sociological theory of structuration focuses on the societal or cultural level. The theory of instrumental genesis can more naturally be applied to the small-group collective level central to CSCL, as Investigation 6 does in discussing how triads of students enacted a feature of an argumentation-support software system.

Investigation 6 presents a "theoretically grounded" conception of the artifact-agent connection. A next step would be to explore an empirically grounded analysis of the connection. While Investigation 6 referred to data from a CSCL experiment, it simply used high-level descriptions of the data to illustrate aspects of the theories being described. It will be important to also analyze such data in detail to see if the connections of groups of students to computer-support systems follow the contours of one or more of the three theories, or whether they display different lines of development. Furthermore, it will be useful to consider more complex technologies, whole meso-level infrastructures [Investigation 3] rather than isolated functions. For instance, in an online course, small groups may have to negotiate the coordinated use of hundreds of functions in Blackboard, Google search, Wikipedia, Facebook, Google Docs, iChat, Gmail, Word and PowerPoint in order to produce a one-week assignment. Such an undertaking invokes the use of individual experience or expertise, established social practices in the school culture, consideration of course requirements and project goals, as well as collaborative discourse and trials by the small groups. The resultant computer-supported effort assembles and interprets a complex technical infrastructure, increases the expertise of the group participants, and provides a medium for group knowledge building. The connection of the collaborative group with the technical infrastructure continuously evolves through use during an academic term.

Having glimpsed the potential relevance of the theory of instrumental genesis to CSCL, issue *7*(2) of *ijCSCL* turns next to a discussion of that theory within the context of CSCL system design. Lonchamp (2012) argues for applying Rabardel's theory by expanding Engeström's (1987) Activity Theory triangle of mediations, to explicitly represent both the processes of mutual shaping of agent and artifact and the specific role of the teacher in CSCL classrooms: He pictures the various mediated interconnections among tool, designer, teacher, student, peer and tutor. Furthermore, he discusses how the agent-artifact connection—embodied in Rabardel's conception of the instrument—evolves over time through usage and re-design.

Lonchamp's paper concludes with a review of CSCL system-design approaches to supporting "instrumentalization" by teachers and students. Although it comes close to describing design-based research (Brown, 1992; DBR Collective, 2003), this review does not name it. DBR is a dominant approach within CSCL research to integrating system design, usage analysis, educational research and practical classroom interventions. It was developed in response to the need to conduct user-centered design of innovative educational software for collaborative groups—a realm lacking in detailed theories, specific analysis methods, adequate software or design guidelines. Perhaps an explicit combination of Rabardel's theory with data from DBR projects could provide empirically grounded insights into the mutual shaping of CSCL software and group cognition in on-going design and usage processes.

The third paper in *ijCSCL 7*(2) is Investigation 7. It situates Rabardel's theory within the context of knowledge-building practices, as these are conceptualized in recent work at the Scandinavian-led Knowledge Practices Laboratory (KP-Lab). This context is populated with social practices grounded in knowledge-building artifacts (Hakkarainen, 2009) and structured in space and time by chronotypes (Ligorio & Ritella, 2010). The knowledge-building artifacts are instruments in Rabardel's sense; they provide for advanced forms of Vygotskian double stimulation (Lund & Rasmussen, 2008). The whole context is the result of the cultural evolution (Donald, 1991; 2001) that led up to our involvement with digital information and communication technologies in an increasingly powerful, distributed and mediated cognitive universe.

From prehistoric times to the present, the proliferation of forms of inscription (Latour, 1990) transformed the human cognitive architecture as profoundly as earlier leaps in biological evolution, allowing radical externalization and collectivization of cognition. In a sense, CSCL aims to push this further, designing collaboration media to foster group cognition that can lead to new forms of individual learning, team knowledge building and community social practices. To the extent that this is true, we need to design new tasks for computer-supported teams, aiming for cognitive achievements beyond the reach of individual team members without computer supports. The goal of CSCL research should not be to simply demonstrate repeatedly that individuals learn better in online groups, but to design and investigate tasks that go beyond traditional instruction. Recent findings concerning "productive failure" (Kapur & Kinzer, 2009) illustrate how groups with challenging tasks may be learning in ways that defy standard testing indicators, but that contribute to increased problem-solving skills of the groups and ultimately of their members.

The analysis of instrumental genesis within the framework of knowledge building points to both the potentials of CSCL and the barriers to widespread dissemination. The historical evolution of tools as "epistemic artifacts" can itself be seen as a knowledge-building accomplishment of the greatest cognitive consequence, related to Vygotsky's—perhaps misleadingly named—notion of "internalization" by individuals of skills germinated in intersubjective circumstances. On the other hand, the complexity involved in successful instrumental genesis translates into severe barriers when, for instance, one tries to promote adoption of CSCL technologies, pedagogies, chronotypes and educational philosophies in established school communities and institutions. Parallel to the difficulties of the students struggling to enact the technological affordances are the difficulties of the researchers, trying to document, analyze and conceptualize the tortuous paths of instrumental genesis in CSCL.

While research on CSCL focuses on the small-group unit of analysis to understand the collaboration, this does not mean that it should ignore processes at the individual or the community levels. Group cognition theory does not ignore individual learning or cultural influences. While many educational researchers inside and outside of the CSCL field have investigated processes at the individual and social levels, few have systematically delved into the relations and influences between these levels, beyond hypothesizing relationships based on common sense presuppositions.

Traversing Planes of Learning

Planes of Learning in CSCL

Learning, cognition and knowledge building can be studied at multiple units of analysis. For instance, analyses of CSCL are often conducted on one of three levels: individual learning, small-group cognition or community knowledge building. One can identify and analyze important processes taking place at each of these levels of description. This tri-partite distinction is grounded in the practices of CSCL. With its focus on collaborative learning, CSCL naturally emphasizes providing support for dyads and small groups working together. In practice, CSCL small-group activities are often orchestrated within a classroom context by providing some initial time for individual activities (such as background reading or homework drill), followed by the small-group work, and then culminating in whole-class sharing of group findings. Thus, the typical classroom practices tend to create three distinguishable levels of activity. Often, the teacher sees the group work as a warm-up or stimulation and preparation for the whole-class discussion, facilitated directly by the teacher. Conversely, the importance of testing individual performance and valuing individual learning positions the group work as a training ground for the individual participants, who are then assessed on their own, outside of the collaborative context. In both of these ways, group cognition tends to be treated as secondary to either individual or community goals. By contrast, the role of intersubjective learning is foundational in Vygotsky (1930/1978), the seminal theoretical source for CSCL. Regardless of which is taken as primary, the three planes are actualized in CSCL practice, and the matter of their relative roles and connections becomes subsequently problematic for CSCL theory (Dillenbourg et al., 1996; Rogoff, 1995; Stahl, 2006).

While these different units, levels, dimensions or planes are intrinsically intertwined, published research efforts generally focus on only one of them and current analytic methodologies are designed for only one. Furthermore, there is little theoretical understanding of how the different planes are connected. To the extent that researchers discuss the connections among levels, they rely upon commonsensical notions of socialization and enculturation—popularizations of traditional social science. There are few explicit empirical analyses of the connections, and it is even hard to find data that would lend itself to conducting such analyses.

The individual student is the traditional default unit of analysis. This assumed approach is supported by widespread training of researchers in the standard methods of psychology and education. In the era of cognitive science, analysis made heavy usage of mental models and representations in the minds of individuals (Gardner, 1985). With the "turn to practice" (Lave & Wenger, 1991; Schatzki, Knorr Cetina & Savigny, 2001), the focus shifted to processes within communities-of-practice. Group cognition lies in the less-well-charted middle ground. It involves the semantics, syntax and pragmatics of natural language, gestures, inscriptions, etc. The meaning-making processes of small-group interaction involve inputs from individuals, based on their interpretation of the on-going context (Stahl, 2006, esp. Ch. 16). They also take into account the larger social/historical/cultural/linguistic context, which they can reproduce and modify.

Computer technologies play a central role in mediating the multi-level, intertwined problem-solving, content-acquiring and knowledge-building processes that take place in CSCL settings. From a CSCL perspective, innovative technologies should be designed to support this mediation. This involves considering within the design process of collaboration environments how to prepare groups, individuals and communities to take advantage of the designed functionality and to promote learning on all planes—e.g., through the provision of resources for teacher professional development, scripted collaboration activities and student curriculum.

The Theory of Interconnected Planes

How are the major planes of learning connected; how can we connect investigations at different units of analysis? To consider a more intuitive physical case initially, a highway ramp or bridge often creates a possibility that did not otherwise exist for going from one level to another at a given point. To traverse from a local road to a limited-access expressway, one must first find an available on-ramp. To cross a river from one side to the other, one may need a bridge. This is the individual driver's view. From a different vantage point—the perspective of the resource itself—the ramp or the bridge "affords" connecting the levels (Bonderup Dohn, 2009).

By "affords" we do not simply mean that the connecting is a happy characteristic or accidental attribute of the bridge, but that the bridge, by its very nature and design, "opens up" a connection, which connects the banks of the river it spans. In his early work, Heidegger analyzed how the meaning of a tool was determined by the utility of the tool to the human user, within the network of meaning associated with that person's life and world; in his later writings, he shifted perspective to focus on things like bridges, paintings, sculptures, pitchers and temples in terms of how they themselves opened up new worlds, in which people could then dwell. In considering the intersubjective world in which collaboration takes place on multiple connected levels, we might say that the work of artifacts like bridges is to contribute the spanning of shores within the way that the world through which we travel together is opened up as a shared landscape of places and resources for meaningful discourse and action.

This transformation of perspective away from a human-centered or individual-mind-centered approach became characteristic for innovative theories in the second half of the 20th Century. It is a shift away from the individualistic, psychological view to a concern with how language, tools and other resources of our social life work. It is a post-cognitive move since it rejects the central role of mental models, representations and computations [Investigation 15]. The things themselves have effective affordances; it is not just a matter of how humans manipulate mental models in which the things are re-presented to the mind. In phenomenology, Husserl (1929) called for a return to "the things themselves" (*die Sache selbst*) and Heidegger (1950) analyzed "the thing" (*das Ding*) separate from our representation of it. In ethnomethodology, Garfinkel and Sacks (1970) followed Wittgenstein's (1953) linguistic turn to focus on the language games of words and the use of conversational resources (Stahl, 2006, Ch. 18). In distributed cognition, Hutchins (1996) analyzed the encapsulation of historical cognition in technological instruments. In actor-network theory, Latour (1990) uncovered the agency of various kinds of objects in how they move across levels in enacting social transformations. Vygotsky (1930) used the term "artifact" to refer to both tools and language as mediators of human cognition. The broader term "resource" is frequently used in sociocultural analysis (Furberg, Kluge & Ludvigsen, 2013; Linell, 2001; Suchman, 1987) for entities referenced in discourse. Such artifacts or resources are identifiable units of the physical world (including audible speech and physical gesture) that are involved in meaning-making practices—bridging the classical mind/body divide.

A central research issue for CSCL is how collaborative knowledge building takes place. The main problem seems to be to understand the role of individual cognition and of societal institutions in small-group meaning-making processes. Figure 1 indicates (without claiming to explain or model) some typical processes on each of the primary planes of learning in CSCL and suggests possible paths of influence or connection, as events unfolding on the different planes interpenetrate each other. This figure is not meant to reify different levels or activities, but to sketch some of the constraints between different phenomena and possible flows of influence. The distinctions represented by boxes and arrows in the chart are intended to operationalize an infinitely complex and subtle matter for purposes of concrete analytic work by CSCL researchers.

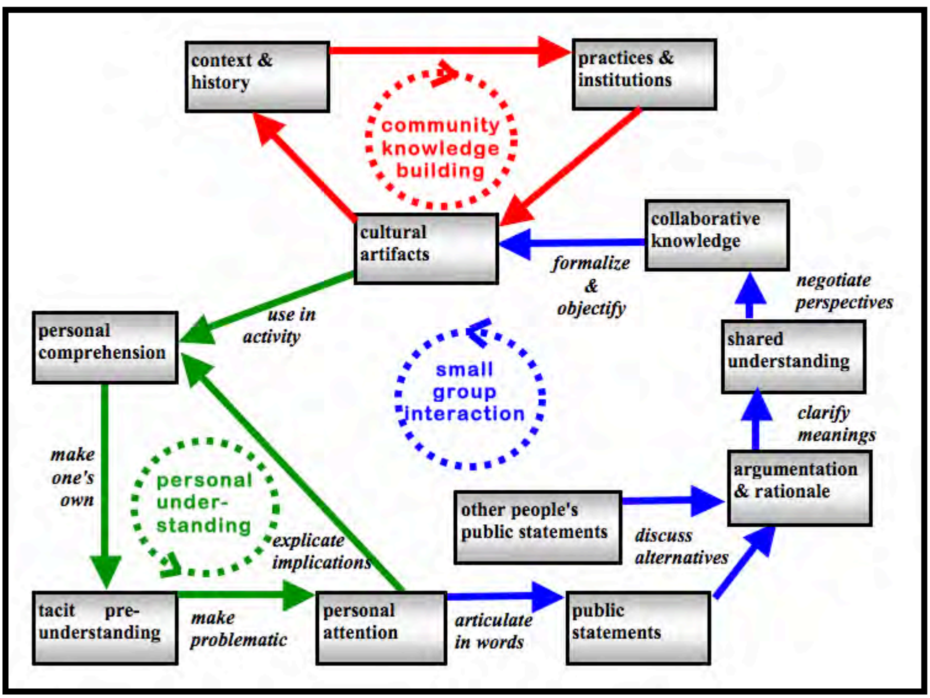

Figure 1. A model of collaborative knowledge building. Adapted from (Stahl, 2006, Ch. 9).

Some researchers, such as many ethnomethodologists, argue against distinguishing levels. For instance, in their description of conversation analysis, Goodwin and Heritage (1990, p. 283) open their presentation with the following claim: "Social interaction is the primordial means through which the business of the social world is transacted, the identities of its participants are affirmed or denied, and its cultures are transmitted, renewed and modified." Social interaction typically takes place in dyads and small groups, so interaction analysis may be considered to be oriented to the small-group unit of analysis. However, CSCL researchers also want to analyze the levels of the individual and the culture as such—e.g., the individual identities and learning changes or the social practices and institutional forces: How do the identities of participants get affirmed or denied as a result of social interaction? How are cultures transmitted, renewed and modified through social interaction?

In general, the sequential small-group interaction brings in resources from the individual, small-group and community planes and involves them in procedures of shared meaning making. This interaction requires co-attention to the resources and thereby shares them among the participants, who co-experience the shared resources. Such a process may result in generating new or modified resources, which can then be retained on the various planes. The resources that are brought in and those that are modified or generated often take the form of designed physical artifacts and sedimented elements of language. We would like to study how this all happens concretely within data collected in CSCL settings.

Resources Across Levels in CSCL

The question of how the local interactional resources that mediate sequential small-group interaction are related to large-scale socio-cultural context as well as to individual learning is an empirical question in each case. There are many ways these connections across levels take place, and it is likely that they often involve mechanisms that are not apparent to participants. In the following, we explore one way of thinking about how such connections can occur: thanks to interactional resources.

In his study of how social institutions can both effect and be affected by small-group interactions, Sawyer (2005, p. 210f) argues that we can conceptualize the interactions between processes at different levels as forms of "collaborative emergence": "During conversational encounters, interactional frames emerge, and these are collective social facts that can be characterized independently of individuals' interpretations of them. Once a frame has emerged, it constrains the possibilities for action." The frames that emerge from small-group interactions can take on institutional or cultural-level powers to influence actions at the individual unit. This interplay among levels involves both *ephemeral* emergents and *stable* emergents. Sawyer's theory of emergents suggests a relationship among different kinds of resources along the lines pictured in Figure 2.

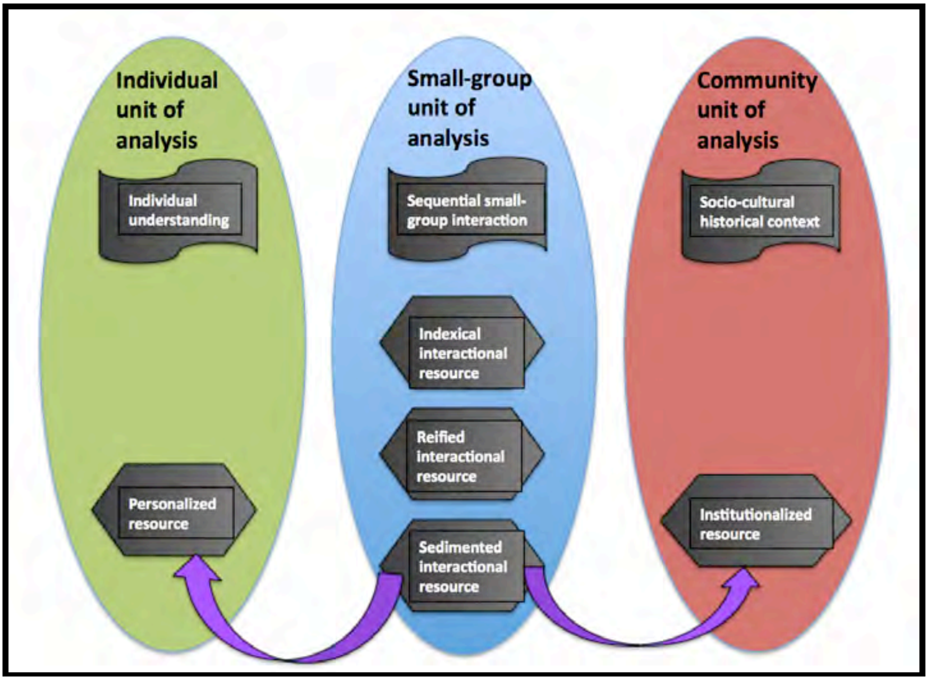

Figure 2. A diagram of emergent interactional resources bridging levels of analysis

While Sawyer's analysis addresses a broad "sociology of social emergence," it can be confined and adapted to the concerns of CSCL. What is most relevant in his theory is the view of emergence arising out of the subtle complexities of language usage and small-group interaction—rather than from the law of large numbers, the interaction of simple rules or the chaotic behavior of non-linear relationships. He thereby rejects the relevance of most popular theories of emergence for CSCL and shifts the focus to the discourse at the small-group unit of analysis. The vast variety of interactional emergents form an intermediate level of analysis between the level of individuals and that of community structures, providing a dynamic and processual understanding of social structures and infrastructures. Analysis focused on these emergent artifacts can deconstruct the reifying processes of emergence that span the group level to both the individual and the social.

The small-group interaction represented in the center of Figure 2 can be theorized as being based on an "indexical ground of deictic reference" (Hanks, 1992). This means that the "common ground" (Clark & Brennan, 1991)—which forms a foundation for mutual understanding of what each other says in conversation—consists of a shared system of *indexical-reference resources*, such as deictic pronouns, which are used to point to unstated topics or resources. The coherence of the interaction and its comprehensibility to the group participants is supported by a network of references, each of which is defined indexically, that is by a pointing within the on-going discourse context ("here," "it," "now," "that point"). Interactional resources, which can be indexically referenced in the interaction, can typically only be understood within their discourse context, but they facilitate meaning making within that context [Investigation 5 and 19].

Interactional resources can undergo a process like Rabardel's instrumental genesis [Investigations 6 and 7]. They may initially be constituted as an object of repeated discussion—an interaction frame (Goffman, 1974)—which we might call a *reified resource*, something capable of being picked out as having at least an "ephemeral-emergent" existence. Through repetition within a group discussion, a term or the use of an object might take on a settled significance within the group's current work. Over time, continued usage can result in a *sedimented resource*, something whose existence has settled into a longer-term "stable-emergent" form, which retains its meaning across multiple group interactions.

A sedimented resource is susceptible to being taken up by a larger community as an *institutionalized resource* within a structured network of such resources, as in Latour's (2007) social-actor networks, contributing to the socio-cultural-historical context surrounding the interaction. Thus, the institutional resource not only references the social context, but also partially reproduces it in a dialectical relationship of mutual constitution by contributing a new element or revitalizing an old set of resources.

On the other hand, interactional resources at various degrees of reification can also be taken up into the individual understanding of community members as *personalized resources*, integrated more or less into the intra-personal perspective of one or more group members. The personalization of previously inter-personal resources by individuals renders them into resources that can be referenced in activities of individual understanding—corresponding to processes of micro-genesis in Vygotskian internalization.

The various components of this view of interactional resources have been hinted at in previous theoretical contributions grounded in empirical examples. The progressively emergent character of resources can be seen even in fields of mathematics and science, as documented in Investigations in this volume.

The term "reification" goes back to Hegel's dialectical philosophy of mediation (Hegel, 1807). Sfard (Sfard, 2000; 2008; Sfard & Linchevski, 1994) has applied it to the formation of mathematical concepts. Husserl (1936) argued that the ideas of the early geometers became "sedimented" in the cultural heritage of the field of geometry. Livingston (1999) differentiated discovering a mathematical proof from presenting a proof; a transformational process takes place, in which the byways of exploration and possibly even the key insights are suppressed in favor of conforming to the "institutionalized" template of formal deductive reasoning. Netz (1999) (see also the review by Latour, 2008) documented the important role of a controlled (restricted and reified) vocabulary to the development, dissemination and learning of geometry in ancient Greece. Analogously, Lemke (1993) argued that learning the vocabulary of a scientific domain such as school physics is inseparable from learning the science. Vygotsky (1930, esp. pp. 56f) noted that the micro-genetic processes of "personalizing" a group practice into part of one's individual understanding—which he conceptually collected under the title "internalization"—are lengthy, complex, non-transparent and little understood. These seminal writings name the processes of reification, sedimentation, institutionalization and personalization of interactional resources; their empirical investigation poses a major challenge for CSCL research.

Among the theories influential in CSCL—such as activity theory (Vygotsky), distributed cognition (Hutchins) and actor-network theory (Latour)—artifacts play a central role as resources for thought and action. In the foundations of activity theory, Vygotsky (1930) conceives of artifacts as including language as well as tools. In his seminal study of distributed cognition, Hutchins (1996) analyzes how the complex of navigational tools, naval procedures for trained teams of people and specialized language work together to accomplish cognitive tasks like ship navigation. He even analyzes data to show how an indexical phrase becomes reified within a dyad's interaction to take on significance that could have led to intra-personal and/or institutional usage. In a witty essay, Latour (1992) shows how a common mechanical door-closer artifact can act to fill the role of an individual person (a doorman), to participate in the politics of a group and to enforce institutional rules. He also argues (Latour, 1990) that an inscription artifact like a map on paper can traverse levels from a local discussion in ancient Asia to the social niveau of imperial Europe. However, studies like these have not often been duplicated in the CSCL literature.

Reviews of CSCL research (Arnseth & Ludvigsen, 2006; Jeong & Hmelo-Silver, 2010) show that few papers in our field have bridged multiple levels of analysis. Yet, the desired CSCL research agenda (Krange & Ludvigsen, 2008; Stahl, Koschmann & Suthers, 2006; Suthers, 2006) calls for a study of representational artifacts and other resources that traverse between individual, small-group and community processes to mediate meaning making. The preceding sketch of a theory of emergent forms of evolving resources could be taken as a refinement of the research agenda for the field of CSCL: a hypothesis about how levels in the analysis of learning are connected; and an agenda for exploration. A number of Investigations in this volume can be read as beginning such an undertaking. They present examples of interactional resources in small-group discussions and indicate how the resources can be seen as bridging levels of analysis.

Resources for Collaboration and for Mathematics

The idea of viewing interactional resources as central to mathematical discourse around dynamic geometry is proposed in Investigation 9, the first article in *ijCSCL* 2013 issue *8*(3). It argues that rather than focusing on the "coordination of interaction" [Interaction 12], collaborative activity should be analyzed in terms of the "coordinated use of resources." Participants rely on two major categories of resources when working on a geometry problem within a computer-based dynamic-geometry environment: (1) mathematical and tool-enabled resources (math-content-related) and (2) collaboration resources (relational or social). In Investigation 9, Öner proposes a focus on the coordination of these resources—which characterize collaborative dynamic-geometry problem solving—for understanding what goes on in such productive math learning.

The combination of social and content resources brought to bear on geometric problem solving often bridges levels. Social resources—such as greetings, invitations to speak, checks on discourse direction—function to cohere the group out of its individual members, drawing upon community standards and institutional routines. Uses of math resources—such as manipulating visual representations, referencing recent findings, expressing relationships symbolically—move fluidly between individual perceptual behavior, group problem-solving sequences and the cultural stockpile of mathematical knowledge. Perhaps the incessant traversal of levels is particularly visible in collaborative math discourse because of its explicit use of multiple layers of reality: a physical drawing, the intended figure, a narrative description, a symbolic expression, the conceptualization, the mathematical object.

Öner's methodological proposal is to trace both the math-content-related and the social/collaborative/relational resources used by students solving dynamic-geometry problems. Math resources may come from graphical, narrative and symbolic representations or expressions of the math problem or from previous math knowledge of culturally transmitted concepts, theorems, procedures, symbolisms, etc. Social resources include communication practices, such as the rules of conversational discourse (transitivity, sequentiality, shared attention, argumentation, turn taking, repair, etc.).

Öner's Investigation cites a number of distinctions drawn in the CSCL literature for contrasting social/collaborative/relational resources with content-related resources:

- An inter-personal-relations space versus a content space (Barron, 2000);
- Building a joint problem space (JPS) versus solving a problem (Roschelle & Teasley, 1995);
- Temporal dimensions of the JPS versus diachronic content (Sarmiento & Stahl, 2008);
- Text chat versus shared-whiteboard graphics (Çakir, Zemel & Stahl, 2009);
- Project discourse versus mathematical discourse (Evans, Feenstra, Ryon & McNeill, 2011);
- Spatio-graphical observation (SG) versus technical reflection (T) (Laborde, 2004).

The "space" that a group builds up and shares is a structured set of resources gathered by the group (JPS, indexical field, common ground). The resources are "indexical" in the sense that they are only defined within (and thanks to) this constructed space of the specific problem context. Through their discourse, the group compiles these resources as potentially relevant to the problem. In turn, the resources help to define the emergent problem, dialectically.

Öner generated data to explore the interaction of the contrasting dimensions by having two people work together face-to-face in front of a shared computer on a particular dynamic-geometry problem, whose solution required a mix of spatio-graphical observation and technical reflection involving mathematical theory—a mix of SG and T resources, to use the distinction she adopts from Laborde. She uses this distinction among resources to structure her analysis. In doing so, she shows how these various resources bridge the different units of analysis. Resources of *individual* perception (during dragging of geometric objects on the computer screen) feed into the *group* problem solving, just as do references to classical theorems passed down through *cultural* institutions. They make possible and stimulate the group interaction. This analysis provides examples of interactional resources at work in CSCL settings.

By analyzing both social and content resources, Öner shows how interrelated these can be. For instance, at one point in the data, one student says, "now two isosceles, oops, equilateral triangles are formed here." This utterance is deeply indexical. It is pointing to the "here" and "now" of the geometric construction. The student is narrating his work, intersecting two circles to locate the vertices of the desired equilateral triangle (see Figure 3). The method he is using refers back over 2,500 years to Euclid's first proposition, which teaches this construction. It also notes that one could use either of two potential intersections to construct alternative triangles. This leads his partner to see first one of the intersection points and then the other. Öner notes that the two students collaboratively accomplished this construction; in the doing of it, they collectively recalled the procedure, which they had performed in the past but forgotten. She also emphasizes that this utterance includes a self-repair, in which the speaker substitutes a correct term ("equilateral") for an incorrect one—a move she considers social. Repairs are conversational moves aimed at avoiding or correcting potential misunderstandings.

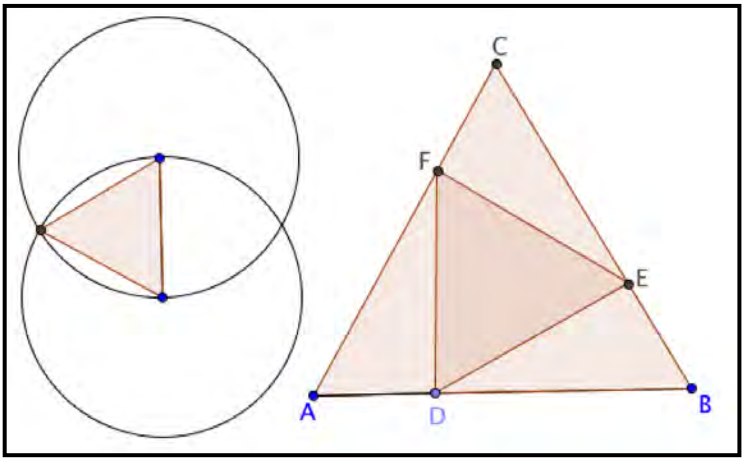

Figure 3. Constructing an equilateral triangle inscribed in an equilateral triangle.

This raises a key theoretical point. Should this utterance be analyzed, categorized or coded as a social resource or as a mathematical one? What is the resource here? Is it the generic conversational resource of self-repair as a "member method" (Garfinkel, 1967), or is it the word "equilateral" in the shared language, or is it the geometric concept of equilateral polygon? I.e., is it a conversational move, a linguistic term or a mathematical concept? This is a matter of level of analysis because one could characterize it in any of these ways. Alternatively, one could argue that the interactional resource that exists here spans multiple levels of analysis, providing an object for analysis at the conversational, linguistic and mathematical levels of the interacting group, the speaking individual and the cultural conceptualization. In other words, such a resource can serve as a boundary object (Star, 1989), which can be discussed from different perspectives, focused on different units of analysis.

Öner succeeds in analyzing how her students collaborated on their geometry problem by focusing consistently on the interplay between social and content resources. It may be that we can often follow the movement of discourses across different levels by keeping our eyes on consequential resources. However, other CSCL researchers interpret the theme of resources differently from Öner. This leads them to different insights about their data. Perhaps we can use the concept of resource as a methodological boundary object to bring together the disparate theoretical voices. Too often, they seem to talk at cross-purposes, emphasizing differences when they might well be seeing the same phenomenon from different angles.

Scientific Representations across Levels

Even if analysts agree in identifying a certain object as a pivotal interactional resource, that does not mean that the nature or meaning of that resource is self-evident to students using it for collaborative learning—as the second article in *ijCSCL* 8(3) by *Anniken Furberg*, *Anders Klug* and *Sten Ludvigsen* (2013) makes clear. They turn to look at how students make sense of scientific diagrams to support their collaborative learning of physics. The implications of a diagram of a photoelectric cell only emerge gradually for a group of students striving to understand and explain the scientific processes represented there.

The central case study of this paper illustrates how the students gradually produce the meaning of the scientific representation. It is the sense-making process—mediated by the representational resource—that spans levels: The individuals, each with their own approaches and each bringing in different other resources, contribute to the group's collaborative effort, resulting in a group understanding, expressed however awkwardly and partially in their written report. The representation—first from their textbook and then complemented with a second diagram from the Internet—is a contribution from the larger scientific or science-education community.

The paper characterizes the science diagram as a *structuring resource*. It argues that the representation, as it becomes meaningful to the students, structures the group's sense-making work. The structuring takes place on various levels: Interactionally, the group uses the diagram as a deictic resource, pointing to its features either gesturally or linguistically to support the verbal accounts. Individually, the students refer to the diagrams to monitor their own understanding. At the level of science norms, the students attempt to use canonical language to express the sense they are making of the diagram.

Student discourse generally halts in articulation of an idea at the point when everyone seems to understand each other adequately for all practical purposes of the conversation. Even adding a third person to the discourse can extend the discussion somewhat, because the third person brings new questions and needs for understanding. However, when students go to write up a point, they must attain a much higher standard of articulation. They must make their written statement comprehensible and persuasive for a general audience or for people not present to indicate their understanding or agreement. This audience might, for instance, include the teacher, other students in the class or even an audience of unknown potential readers. The audience might require a scientific formulation, using the vocabulary and stylistic genre of physics. Furthermore, since the reading audience is not co-present with the speakers, physical gestures and deictic references to times, places, people and objects present are no longer effective. While the diagram still helps to structure their articulation of the description, the description can no longer rely so heavily on the diagram to help convey their meaning.

It is always true that there is a dialectical circularity or recursive character to the relationship of the discourse context and the utterances that are made within that context; this becomes even clearer in the relationship of the diagram as a structuring and interactional resource to the students' understanding of this resource. The (tentatively understood) diagram helps to structure the students' (increasing) understanding of the diagram itself. The paper nicely shows how the introduction of a second diagram enriches the dialectic by shedding light on the first diagram's meaning through the tension created by the differences between the two representations.

Referential Resources for a Math Problem

In the third paper of *ijCSCL* 8(3), Investigation 5 takes an ethnomethodologically informed look at the role of resources, representations, referential practices and indexical properties in the mathematical problem-solving interactions of students within a CSCL setting. Viewed in the context of the 8(3) issue of *ijCSCL*, Investigation 5 develops further some of the central themes of the two previous papers. It concurs with the first paper on the importance of tracking the use of resources, and it further emphasizes that it is the on-going specification-in-use that determines the significance of a given resource. It concurs with the second, in adopting a concern with representations, and it makes even more explicit the extent to which the representational practices—how the representation was built and worked with—contribute to the problem clarification and problem solution.

In theoretical terms, this paper develops the discussion of *indexical reference resources* by Hanks (1992). It considers two groups of students who were presented with the same problem statement involving combinatorics. The two groups identified completely different sets of "indexical properties," which allowed them to formulate implicitly, share collaboratively and solve mathematically the "same" problem, which, however, had been specified quite differently. In the first team, Bwang8 specified the stair-step pattern of squares in terms of two symmetric sets of lines. Each set of lines followed the pattern: 1, 2, 3, …, n, n. In the second team, Davidcyl specified the problem initially as: "the n^{th} pattern has n more squares than the $(n-1)^{th}$ pattern."

Ethnomethodologists are keen to observe the "work" that people do to accomplish what they do. Both teams engaged in intricate coordination of text understanding, sequential drawing, retroactive narrative and symbolic manipulation to make sense of the problem statement they faced and to arrive at a mathematical solution. The work involved in this can be characterized as discovering, proposing and negotiating successive determinations of indexical properties of the problem they were working on. The indexical properties are ways in which the team members can reference aspects of the problem, such as in terms of sets of lines arrayed in specific identifiable patterns. These indexical properties are tied to the local problem-solving context of the respective team. They specify the problem for the team in practical terms, which allow the team to make progress in both understanding and solving the problem.

This approach is appropriate for what Rittel and Webber (1984) called "wicked problems." These are non-standard problems, for which the approach to problem solving is not obvious and turns out to be a matter of coming to understand the problem itself. One can imagine Bwang8 entering a completely unknown territory. He was not familiar with the online environment, had never seen the kind of problem statement that was displayed, did not know the other team members and was unclear about what was expected of him. He spotted (visually) an interesting symmetry in the problem and started by stating it as an initial specification about how to view (perceptually and conceptually) the problem. Then he started to draw the problem, so specified, on the shared whiteboard. Davidcyl entered a similarly unknown territory. He started drawing the pattern for N=4, as suggested in the text. In so doing, he developed some copy-and-paste practices, which he presented (in the sequentiality of his drawing process as well as in his accompanying description) as tentatively mathematically relevant.

Starting from *individual* suggestions of indexical properties (by Bwang8 or Davidcyl, respectively), each group developed a growing shared indexical ground of deictic reference. The work of building that space of possible references led the *group* to make sense of a problem and to discover a path to a solution in mathematical terms. The ground itself is a set of shared interactional resources that allows the team to refer to its object of concern in mutually intelligible ways. By gradually moving from purely deictic terms like "it" or "this," to mathematical terms or abstract symbols, the indexical resources incorporated cultural knowledge and contributed to a less locally situated store of understanding that could be relevant in a larger classroom or *culture* of school mathematics (including standardized tests). The analysis of how these groups successively and collaboratively re-specify their referential resources suggests approaches to studying how groups make sense of problems and artifacts whose indexical properties are initially unknown or underspecified. This is a foundational concern for CSCL, as "a field of study centrally concerned with meaning and the practices of meaning making in the context of joint activity, and the ways in which these practices are mediated through designed artifacts" (Koschmann, 2002).

Roles as Interactional Resources for Community Meaning Making

If the previous studies take interactional approaches, the next paper in *ijCSCL* 8(3), Hontvedt and Arnseth (2013), can be considered to be largely at the community-of-practice level. Like the apprenticeship cases of Lave and Wenger (1991), this one is concerned with how novices take on the practices of a professional community. Situated in a simulator for training Norwegian sailors, the apprentices role-play at navigating a ship. To bring a ship up the fjord to Oslo, they must bring aboard a local expert. This master pilot helps to establish the professional navigational practices with the apprentices. Interestingly, the pilot insists on using the international language of shipping, English. At times, the trainees slip into Norwegian to reflect on their role-playing, thus marking linguistically the duality of their realities. On the one hand, they are playing the roles of professional sailors interacting in English on the bridge with the local pilot; on the other, they are Norwegian students discussing their educational activities.

Through their role-playing, the participants—whether newcomers or established members of the sailing community—co-create interactionally the context of their learning. Much of the learning consists in this subtle process, which includes integrating interpersonal relations, language constructs, physical artifacts, a designed setting and nautical tasks. Together, this constitutes what the authors call an *activity context*. Building on the theoretical framework of activity theory, an activity context is closely related to Goffman's (1974) concept of frame.

The roles taken on by the students are resources for their apprenticeship meaning making. Like roles in a play on stage, they require a willing suspension of disbelief. The analysis in the paper nicely shows how the students fluidly move in and out of their roles and negotiate when to do so, often through code switching between the languages of the two cultures. Never taking the simulation fiction too seriously—as though it were an immutable reality—the analysis reveals how the participants themselves achieve the tenuous existence of the activity context interactionally.

The interactional resources of this learning community are ephemeral emergents—which also means they can collapse. The action can call for a role or an artifact that is missing from the simulation, resulting in improvisation, chaos, laughter. This carries a lesson for all of us: an assemblage of resources for learning cannot foresee all uses. Even the most rehearsed experiment in complex learning is likely to run afoul of glitches. In the best cases, the participants laugh off the troubles … and the analysts discover insights in the breakdowns.

Annotations as Resources for Individual Learning

In the final paper of issue *ijCSCL 8*(3), Eryilmaz et al. (2013) take a controlled-experiment approach to evaluate the effect of a promising annotation-support tool as a resource for individual learning. While acknowledging that online asynchronous discussion in a university course is a group activity in an educational social setting (with an instructor, discourse standards, canonical texts, grading, etc.), the authors systematically focus on the learning of individual students as evidenced by their individual postings and isolated pre-/post-tests. In contrast to the qualitative analysis of interaction in the preceding papers, this one codes individual posts and analyzes them with a battery of quantitative methods. Even the analysis of sequentiality is done without reference to interactional context. The group and social setting are considered controlled for, and only the presence of the software function distinguishes the treatment from the control condition.

By methodologically focusing on the individual student and the individual posting as the units of analysis, this study is able to isolate and quantitatively assess the role of context on these units. For instance, the paper asserts that, "collaborating students are able to use one another as a *resource for learning*" (emphasis added). That is, while learning is conceptualized as a process that primarily takes place in individual heads, it is enhanced by the interactional level of individuals formulating ideas as posted text and receiving feedback as posted responses from others. Asynchronous discussion forums seem like good media for supporting such enhancement, except that their use apparently causes excessive "cognitive load," reducing the ability to engage in the cognitive processes required for deep learning and therefore counteracting the potential benefits of social interaction.

The complex socio-cultural and interactional processes analyzed in the previous papers are here viewed as likely sources of unwelcome cognitive load. In order to communicate one's ideas about a text in annotations that might make sense to other students, one must engage in the sorts of collaborative meaning making analyzed in the other papers. For instance, one must construct explicit indexical references, such as "the third sentence in the conclusion," which can be used to coordinate co-attention.

To make it easier to establish joint reference, the authors of this study provided students with a software indexing function, which graphically connects annotations with relevant selections in the provided educational text. The treatment group uses this software tool as an *interactional resource*, which is not made available to the control group. The research then studies the effect of the resource on learning with the rigor of its chosen methodology. The study shows that the treatment group produces more posts coded as "assertions" and "conflicts." It also does better than the control on the post-test, confirming experimental hypotheses. The conclusion is that the software resource reduced the cognitive load needed to co-construct effective shared interactional resources, like indexical descriptions of target text passages. This allowed the students more cognitive ability—or perhaps just more time-on-task—to engage in interactive assertions and conflicts. So, the focus on the individual unit of analysis allowed this study to evaluate interactions between individual learning, group interaction and socio-technical setting.

Of course, one can always question a study's assumptions and operationalization. The recent findings in CSCL research about "productive failure" (Kapur & Bielaczyck, 2012; Kapur & Kinzer, 2009; Pathak et al., 2011) problematize the purely negative view of what is here characterized as cognitive load, as well as the way of assessing deep learning. Positive findings about productive failure suggest that group processes can underlie learning in ways that may not show up immediately. The effort (cognitive load) to build a joint problem space about a text through interpersonal interaction may confer learning benefits that are not achieved when that task is delegated to software. The benefits may also not show up in measurements taken immediately at the individual unit of analysis.

This final paper of the *ijCSCL* issue, taken together with the preceding four, illustrates how different methodologies can be adopted for analyzing resources and their relations to different levels of analysis. What can be taken as a resource for purposes of CSCL research is open to a broad range of approaches and theoretical frameworks. One can find resources for individuals, groups and communities. Often, those resources can be seen as traversing across or mediating between levels. Analysts can fruitfully focus on one aspect or another of this; or they can strive to follow resources across multiple levels.

The CSCL Agenda on Levels of Analysis

The time has come for CSCL to address the problem of traversing levels of analysis with exacting research. Attempts to research a given level in isolation have run into fundamental limitations. Although it is clear to most researchers that the levels of individual, small-group and community phenomena are inextricably intertwined, opinions differ on how to respond analytically. Religious wars between adherents of different methodological faiths are often based on misunderstandings: people agree on the need to comprehend the levels together, but articulate that need in incommensurate-seeming locutions.

Multiple-method approaches, multi-level statistics and multi-vocal analyses are too limited, because they do not explicitly address the interrelationships among different levels. Some researchers claim that the apparent levels are all reducible to one fundamental level—whether individual cognition, group interaction or the social—while others assume that they can be studied independently. Some say that there is no such thing as different levels, but only different kinds of analysis, although they generally end up talking of individual understandings, group interactions and community practices. There are vague theories that one level is emergent from another or dialectically coupled with it, but these ties are not well worked out or evidenced with CSCL data.

The contributions in issue *ijCSCL 8*(3), provide examples of the kinds of studies and analyses that are needed. In order to comply with one or another standard of rigor, most research focuses on specific relationships within a single unit of analysis. We now also need to generate, compile and analyze data that sheds light on relationships across levels. The idea of tracking *interactional resources* as they mediate across levels offers one suggestive approach. The different papers discussed here and other referenced theories show that there are many ways to conceptualize, analyze and theorize resources. We do not mean to define or defend a particular tack, but to suggest interactional resources as a candidate boundary object for discussion across competing approaches. We do not claim to have proposed a consistent position, but rather to raise some questions about what can be meant by resources for computer-supported collaborative learning, in the hope of stimulating thinking for CSCL research in the future.

This Investigation has tried to prepare the way for the more detailed considerations of a theory of group cognition in this volume, especially the essays of Part III. After tracing the historical expansion of the concept of cognition–especially in twentieth-century philosophy—from individual minds to group and collective cognition, it focused on the concept of intersubjectivity as central to analyzing and designing collaborative learning. Intersubjectivity is the ability of multiple subjects to understand each other by interacting within a shared world. A number of approaches to intersubjective meaning making were reviewed, including by CSCL researchers, philosophers, ethnomethodologists and activity theorists. The intersubjective processes at the small-group unit of analysis were seen as intimately connected with the adoption and use of artifacts and social practices. This led to consideration of the inherent integration of multiple planes of learning and the role of resources that span the individual, group and cultural levels. These themes are explored at length by the Investigations of Part II and Part III, which follow. They provide detailed arguments and clarifications for the vision of CSCL proposed in Investigation 1, with its theoretical, methodological and pedagogical focus on the intersubjective small group.

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9. A Post-cognitive Theoretical Paradigm

Abstract. This essay poses the question: Can CSCL represent a new paradigm of educational research within the Learning Sciences? It begins by looking at the historical relationship of the two related research communities: Computer-Supported Collaborative Learning and the Learning Sciences. It presents them from the perspective of the author as a participant in those communities during 20 years (1995-2015). It reviews the institutional history of their relationship within the International Society of the Learning Sciences. Trends in the history of philosophy and social theory are then reviewed to motivate an innovative contemporary paradigm. A "post-cognitive" educational paradigm is proposed that focuses on group interaction as the unit of analysis that is most central to CSCL. Finally, the author's CSCL research agenda is described as an illustration of a candidate approach. In conclusion, it is proposed that CSCL research should focus on the analysis of group processes and practices, and that the analysis at this level could be considered foundational for the Learning Sciences.

Keywords. Post-cognitive, educational paradigm, research community, shared understanding, collective intentionality, group agency.

A Participant's View of LS and CSCL

The Learning Sciences (LS) and Computer-Supported Collaborative Learning (CSCL) are not easy to clearly distinguish. There are no objective or fixed definitions of these two fields. They are best understood as communities of researchers. Despite their fluidity, they do seem to evolve in a certain direction over time. The shifting nature of the communities appears differently to different participants and is often negotiated in discussions among them. In this essay, I discuss the CSCL and LS communities from the perspective of my own participation in them. I start with some personal and community background because research is always oriented in response to personal and political commitments of the people and communities involved. This does not contradict the "objectivity" of the research—for it must still meet accepted standards of rigor and accept the implications of scientific findings—but provides a context of significance necessary for relevance, motivation and shared understanding. Theory is always situated.

CSCL is trans-disciplinary, requiring a mix of academic backgrounds. I came to CSCL from philosophy and computer science. In the 1960s and early 1970s, I studied twentieth-century continental philosophy and social theory at MIT, Northwestern, Heidelberg and Frankfurt, but supported myself as a math teacher and computer programmer. In the early 1990s, I studied computer science academically, specializing in AI, design theory, HCI and CSCW at the University of Colorado in Boulder. Upon graduation in 1993, I decided to apply computer science to educational innovation. When Tim Koschmann spent a year at Boulder during 1997/98 while I was starting my career as a research professor, I participated in his course on CSCL and he introduced me to local conversation analysts, whose courses I also attended. Koschmann was instrumental in organizing the first seven CSCL conferences and editing the seminal CSCL book (Koschmann, 1996). I participated in all the CSCL conferences, starting in 1995, and also the ICLS conferences from 1998 on. During 2001/02, I lived in Germany for a year and worked on a European Union CSCL research project. That year, I met many of the Europeans active in the CSCL community and visited their labs, workshops and conferences.

Koschmann convinced me to be program chair of CSCL 2002 in Boulder. At the closing session of CSCL 2002, those present agreed to found a new organization, the International Society of the Learning Sciences (ISLS), to provide an institutional framework to bring together the CSCL and ICLS conference series and also the *Journal of the Learning Sciences* (*JLS*). It was decided that Timothy Koschmann, Janet Kolodner and Christopher Hoadley would share leadership of the society. I agreed to be on the founding board, to draft the by-laws, to set up the website and to design a logo.

The contested relationship of CSCL to LS soon flared up at CSCL 2003 in Bergen, when the legal incorporation of ISLS was announced there. The central participants in the CSCL community were largely European members who had been active in the AI-in-Education community. They felt that Roger Shank had betrayed the AI-in-Education community when he hosted their conference at Northwestern in 1991 and used that occasion to proclaim himself the leader of a new field, which he called "the learning sciences." Kolodner was seen as his protégée, who had extended his technical contribution in AI models of case-based reasoning and was the founding editor of *JLS*, the journal of LS. At the time, virtually all articles in *JLS* had been by North American authors and represented a strongly cognitivist approach. The International Conference of the Learning Sciences (ICLS), the conference series for LS, was held exclusively in the US until 2008, and had been dominated by a few American schools, primarily prestigious departments of education at US universities (e.g., Northwestern, Georgia Tech, Michigan, Washington, UCLA, Indiana, Berkeley, Stanford, Vanderbilt, Pittsburgh).

So, at the Bergen conference, a group of European CSCL researchers raised harsh questions about whether ISLS was an attempt by American LS leaders to take over the field of CSCL and its conference series, which was finally being held in Europe in 2003—after Euro-CSCL 2001 in Maastricht was retroactively recognized as an official CSCL conference. Kolodner, Koschmann and Hoadley were unable to satisfy the concerns raised. There was lively discussion among the conference attendees, and a smaller group of us drafted a position paper overnight. The outcome was to proceed with the establishment of ISLS, but to set up a CSCL Committee within ISLS to represent the CSCL community. The CSCL Committee would exercise control over CSCL matters, like the CSCL conference series. During the same conference, the idea of a CSCL journal (*ijCSCL*) was proposed; Hans Spada suggested that I found it with the co-editorship of Friedrich Hesse. Pierre Dillenbourg had already established a CSCL book series published by Springer. These initiatives helped to form links and establish parity between LS and CSCL.

ISLS gradually became established. Hoadley was the first President, and subsequent presidents included several prominent European and American CSCL researchers, including some who had raised the original critical questions at the 2003 conference in Bergen, Norway. Kolodner served as Executive Director of ISLS throughout its formative years. The tension between CSCL and LS gradually dissipated; the CSCL Committee lingered on, primarily playing a symbolic role. ISLS, ICLS and *JLS* gradually made concerted efforts to become more international and to broaden their leadership. Although the assumption has generally been that the two communities have largely merged, my sense is that the theoretical differences between them and between the two conference series have not much altered during the intervening decade. The conflict between CSCL and LS may have been more than a political clash between overlapping communities; it may also represent a rejection by many CSCL researchers of the extreme commitment to cognitivist theory and methodology by prominent LS proponents at that time.

It is hard to define the difference between CSCL and LS other than, perhaps, in terms of the people involved. This is because both communities profess openness to the same range of theoretical and methodological frameworks, although both promote certain preferred orientations in subtle and unspoken ways. For instance, most researchers in both fields claim to accept the situated nature of learning and the sociocultural perspective, but if you look closely at their analyses, you find that they both often rely on methods and approaches that predate and may contradict these theoretical positions. While many researchers publishing in CSCL venues still employ cognitivist methods—such as interpreting isolated utterances as expressions of mental representations, empiricist controlled experiments manipulating objective conditions or coding along predetermined categories—it may be that the CSCL vision calls for a different research paradigm.

Did CSCL or LS Adopt a New Paradigm?

In the introduction to his edited volume of CSCL studies, Koschmann (1996) proclaimed that CSCL provided a new paradigm of research on instructional technology. He used Kuhn's principle that a paradigm must be "sufficiently unprecedented to attract an enduring group of adherents away from competing modes of scientific activity" (Kuhn, 1972, p. 10). A few years later, as Koschmann saw that there was no consistency in method among actual CSCL studies and that the vast majority of CSCL and LS studies had, in fact, not moved away from traditional approaches to measuring individuals' learning outcomes, he reconsidered that claim. He argued that:

> Traditional theories of learning treat learning as a concealed and inferred process, something that "takes place inside the learner and only inside the learner" (Simon, 2001, p. 210). CSCL research has the advantage of studying learning in settings in which learning is observably and accountably embedded in collaborative activity. Our concern, therefore, is with the unfolding process of meaning making within these settings, not so-called "learning outcomes." It is in this way that CSCL research represents a distinctive paradigm within IT. By this standard, a study that attempted to explicate how learners jointly accomplished some form of new learning would be a case of CSCL research, even if they were working in a setting that did not involve technological augmentation. On the other hand, a study that measured the effects of introducing some sort of CSCL application on learning (defined in traditional ways) would not. (Koschmann, 2001, p. 19)

In his keynote talk at CSCL 2002, Koschmann proposed that "CSCL is a field of study centrally concerned with meaning and the practices of meaning making in the context of joint activity, and the ways in which these practices are mediated through designed artifacts" (Koschmann, 2002, p.17). It is important to note that "meaning making" is here taken as an intersubjective or "joint" practice or small-group process. Meaning is not conceived as a mental model somehow existing in the brains of individuals.

Koschmann then reviewed what he took to be a seminal CSCL paper by Jeremy Roschelle (1992) as an early instance of the CSCL paradigm, because Roschelle focused on the analysis of meaning-making practices (such as conversational moves in a dialog) in a context of joint activity (dyads working collaboratively on challenges) mediated by a designed activity (a software simulation of the relationship of velocity and acceleration).

Koschmann focused on the version that Roschelle published in *JLS*—which Koschmann himself later republished in his CSCL edited volume (Roschelle, 1996). However, in terms of the relationship of CSCL and LS, the situation was rather more complicated as well as more interesting than what Koschmann reported. First, Teasley and Roschelle (1993) presented an analysis involving the co-construction of a "joint problem space" (JPS) by students, using Roschelle's dissertation data. The JPS was an explicit transformation of the cognitivist conception of a mental problem space in (Newell & Simon, 1972) into the intersubjective realm of situated interaction. Newell and Simon's notion of cognitive production rules (mental mechanisms) was re-conceptualized by Teasley and Roschelle as socially distributed, turn-taking, collaborative completions (discourse moves). The unit of analysis was transformed from the individual mind to the small group interaction (dialog and joint attention through pointing).

Stephanie Teasley was instrumental in bringing a post-cognitive framework to this analysis in her collaboration with Roschelle, while they were both interns at the Institute for Research on Learning (IRL) in Palo Alto. IRL was a hotbed of post-cognitive innovation, inspired by theories of conversation analysis, ethnomethodology, activity theory, situated action and situated learning. Teasley (then named Behrend) and Roschelle first presented their analysis with co-author Janice Singer at the CSCW 88 and ITS 88 conferences (Behrend, Singer & Roschelle, 1988; Singer, Behrend & Roschelle, 1988). These papers grew into the version later published as (Teasley & Roschelle, 1993), presented at a NATO-sponsored workshop in Italy in 1989 (the first event ever to use the term "CSCL"!).

It was these early versions of the paper that really emphasized the intersubjective practices of meaning making in the context of joint activity. The authors explicitly juxtaposed their perspective to cognitivism: "Thus, in contrast to traditional cognitive psychology, we argue that collaborative problem solving takes place in a negotiated and shared conceptual space, constructed through the external mediational framework of shared language, situation and activity—not merely inside the cognitive contents of each individual's head" (Roschelle & Teasley, 1995, p. 70).

In the *JLS* article reporting on this research, Roschelle argues that the ability of the dyad to "share" knowledge in a cognitive sense (as convergent mental contents) could be demonstrated by an analysis of the collaborative sense in which the students "share" a joint meaningful world (are engaged with co-constructed meanings and artifacts). Tying the analysis of intersubjective meaning making to the problematic of cognitive convergence (as encouraged by *JLS* editor Kolodner) had the potential of appealing to the *JLS* audience, because it put the argument in cognitive terms, they could relate to without disrupting their paradigm. However, this made the argument more complex and detracted from its ability to stand as a clear example of a post-cognitive paradigm.

Koschmann concluded that CSCL could be a new paradigm if studies would maintain a focus on how groups of learners collaboratively achieve new understandings in the presence of computational artifacts. However, in most CSCL studies (as in LS studies) there is a conflict between the espoused and the applied theories of learning or between the motivating theoretical concerns and the bottom-line methods of analysis.

After Roschelle and Teasley's publications, most actual instances of research by the CSCL and LS communities fall back on old traditions in educational psychology or other forms of measuring and correlating learning outcomes of individuals—sometimes despite the researchers' best stated intentions and even the inherent needs of their research questions. (This observation is based on ten years of reviewing all the submissions to *ijCSCL* as well as searching the broader literature for instances of analysis at the group unit of analysis.)

Measuring the effectiveness of dialog or collaboration is never a straightforward affair. It is highly dependent upon the details of the setting and the group practices. Methodological concerns related to this were expressed early in founding documents of CSCL, for instance by Dillenbourg, Baker, Blaye and O'Malley (1996, p. 189). Here they distinguish the CSCL vision of research on "collaborative" learning from the cognitivist tradition of research on "cooperative" learning (e.g., Johnson & Johnson, 1989; Johnson & Johnson, 1999; Slavin, 1980):

> For many years, theories of collaborative learning tended to focus on how *individuals* function in a group. More recently, the focus has shifted so that *the group itself has become the unit of analysis*. In terms of empirical research, the initial goal was to establish whether and under what circumstances collaborative learning was more effective than learning alone. Researchers controlled several independent variables (size of the group, composition of the group, nature of the task, communication media and so on). However, these variables interacted with one another in a way that made it almost impossible to establish causal links between the conditions and the effects of collaboration. Hence, empirical studies have more recently started to focus less on establishing parameters for effective collaboration and more on trying to understand the role that such variables play in mediating interaction. In this essay, we argue that *this shift to a more process-oriented account requires new tools for analyzing and modeling interactions*. (Italics added)

In the first volume of the *International Journal of CSCL* (*ijCSCL*), Suthers (2006, p. 321) [Investigation 4] proposed a research agenda for CSCL: "To study the accomplishment (a post hoc judgment) of intersubjective learning we must necessarily study the practices (the activity itself) of intersubjective meaning making: how people in groups make sense of situations and of each other." He agreed on the need for CSCL research to focus on analysis of group processes. He immediately noted, however, that few studies published in the CSCL literature have addressed *intersubjective* meaning making directly; all but a few analyze data taken as related to individual minds.

The motivating vision of CSCL presented here suggests that research in this field should focus on the small-group unit of analysis. CSCL is a response to the potential of computer technology networked though the Internet to bring learners together and to support their collaborative knowledge building. The potential is not just to provide innovative tools and broadened sources of information to individual learners, but to allow cognition itself to evolve from individual efforts to group efforts [Investigation 7]. The rigorous analysis of computer-supported collaborative learning requires a new research paradigm oriented primarily to the small-group unit of analysis as the locus of intersubjective meaning making.

There are many pressures against research adopting a new paradigm and new tools for analyzing interactions. For one, the study of interaction processes and group practices requires analytic skills that are not generally taught in standard college courses on research methods and statistics. There are also external influences: The public wants stories that meet common-sense images of science based on popular notions of traditional science, such as mechanistic Newtonian physics. Politicians and funding sources want simple numeric results that they can cite as clear measures of return on government or grant investments in education. Academic hiring and promotion committees want publications in well-established conferences and journals to justify their decisions. Conferences and journals rely on peer review by scholars trained in traditional notions of rigor. Systems of social rewards—which largely define behaviors in academic research communities—militate against methodological innovation, even as they reward superficial adherence to the latest trends.

It is hard to determine how many publications in CSCL or LS break free of the cognitivist paradigm's stronghold on publication. For instance, studies of CSCL publications (e.g., Akkerman et al., 2007; Jeong & Hmelo-Silver, 2010; Jeong, Hmelo-Silver & Yu, 2014; Kienle & Wessner, 2006; Lonchamp, 2012; Tang, 2014) bring their own paradigmatic blinders or filters. They sometimes eliminate from consideration any paper that does not focus on "empirical" data analysis, often excluding ethnographic case studies and certainly theoretical articles. They generally miss many of the most influential papers or more innovative approaches. Many highly rated journals in the educational field advertise that they only publish papers that conform to traditional empiricist methodological standards. The stances of these journals in turn influence the attitudes of reviewers for other journals and conferences. Attempts to categorize publications in CSCL and LS often succumb to a similar fate, imposing implicit or explicit criteria on the selection of papers to be categorized.

We have seen that it is hard to determine the extent to which a post-cognitive paradigm is making headroads in CSCL and/or LS research. What would a CSCL paradigm look like that systematically thematized the mutual engagement of small groups in meaning making and problem solving, as suggested by Koschmann; Roschelle and Teasley; Suthers; Dillenbourg, Baker, Blaye and O'Malley?

The following sections of this Investigation explore the implications of the post-cognitive theories that are so often espoused within the CSCL and LS communities, but relatively rarely carried through in the published analyses. First, recent post-cognitive theories are traced back to their roots in the history of philosophy, noting the historic junctures that provide the ontological and epistemological motivations for various alternative methodologies. Then, Vygotsky's argument for the foundational role of intersubjective collaborative learning for educational theory is summarized. Next, the nature of a post-cognitive paradigm is illustrated by the example of the VMT CSCL research project. Finally, it is concluded that CSCL should more consistently focus on analysis of group cognition, which, moreover, may be considered foundational for learning generally.

The Post-cognitive Philosophical Paradigm

The post-cognitive CSCL paradigm studies *meaning making as a joint (or group) activity*. For instance, the analysis by Teasley and Roschelle (1993) in terms of the collaborative activity of constructing a joint problem space was an early instance of this new paradigm. However, the analysis of the same data in terms of "cognitive convergence" reduced the meaning making to measures of traditional individual mental phenomena—externally influenced by computer images and internally involving increasingly similar mental representations of those images in the heads of the students.

To grasp the significance of this distinction between cognitive and post-cognitive, consider the schematic history in Figure 1 of a strand within Western philosophy and social theory that contributed to the theoretical foundation of this paradigm shift.

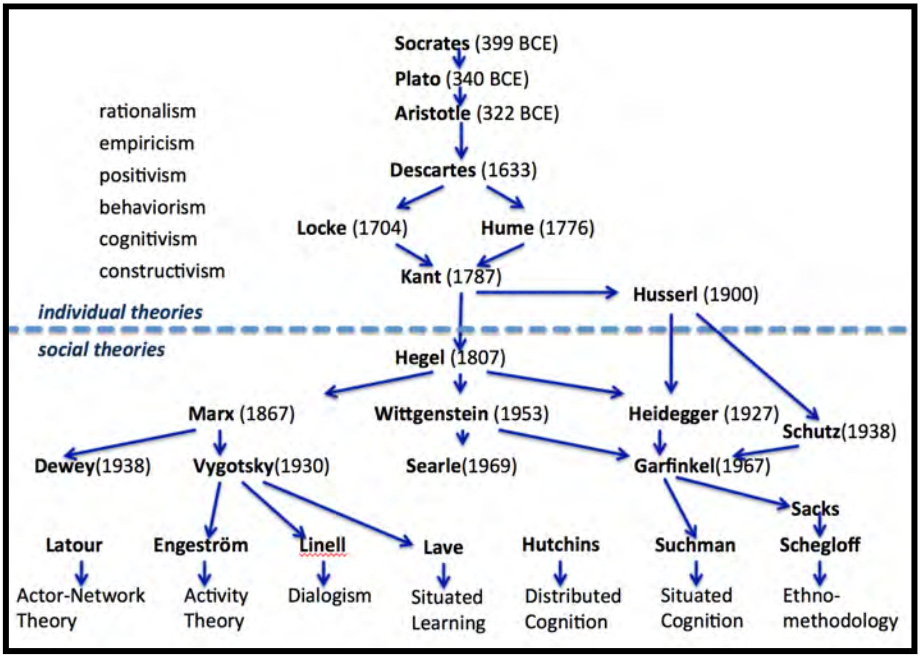

Figure 1. The evolution from individualistic to social theories in philosophy and social science. A major paradigm shift in theory occurred two centuries ago, but has still not affected most CSCL and LS analyses.

Philosophy began with the classic Greeks locating knowledge in eternal ideas, rather than in the social norms of the *polis* or the traditions of mythology. Descartes relocated these ideas in the individual mind, and thereby created the epistemological problem: how can ideas in the mind correspond to valid knowledge of the non-mental world? Locke and Hume gave opposing views in response to Descartes, emphasizing individual human reason or individual human experience. Various mixtures of these philosophies motivated scientific paradigms of rationalism, empiricism, positivism and behaviorism—with their objectivist methods. Kant overcame the conflict between rationalism and empiricism by arguing that the human mind constructs what it can know of the world by structuring sense perception with categories of space, time and causality. Thus, Kant provided the philosophic basis for the paradigms of constructivism and cognitivism: People construct knowledge, so an analysis of human behavior and learning must take into account the role of cognition in making sense of the world (vs. positivism and behaviorism in the human sciences).

Note that up to this point, human nature and human cognition were posited as based in the individual person, as fully determined from birth ahistorically or universally—not dependent on one's biography, growth-related processes or social context. Remember that the views that minds develop (Freud), that social relations transform

(Marx) or that humanity evolves (Darwin) all came after Hegel—inspired by his dynamic philosophy. The outmoded pre-Hegelian, ahistorical view survives in our culture as common sense and as a pervasive ideology of individualism. It also survives in the empiricist and rationalist assumptions about science and research methodology, which persist in positivist notions of objectivity and reductionism to individual cognition.

Hegel (1807/1967) argues that human consciousness emerges through productive activity in the social and physical world: Individuals are formed as such (i.e., as self-conscious individuals) through the interaction with each other and with artifacts (tools and products of work) in the world. Hegel describes the emergence of self-consciousness from within the process of mutual recognition of self and other.

Marx (1867/1976) builds on this analysis of social interaction. He situates Hegel's idealist analysis in the historical context of capitalism. For Marx, individuals in capitalist society are analyzed as results of their interactions as wage laborers, owners of the means of production or consumers of commodities. The "cell form" of social analysis is the interaction between worker and owner that produces artifacts for the market. Marx critiques the traditional notion of the abstract individual as an ideology that obscures concrete human reality as fundamentally social.

In the cognitive paradigm, one assumes that an interaction such as takes place in a CSCL setting can be analyzed in terms of individuals, who can be characterized independently of the interaction context, for instance by characterizing their mental states and internally stored knowledge. The sense making that takes place is attributed to the individuals, who then may compare their private understandings, personal opinions or mental representations. By contrast, in the post-cognitive theories listed across the bottom of Figure 1, interaction is primary. For instance, Linell (2009) describes his post-cognitive dialogical approach as follows:

> In the analysis of sense-making as it occurs in communication and interventions into the world, as well as in solo thinking or the reading of texts, etc., we must start out from the encounters, interactions, events etc. as the basic phenomena; they are primary, not secondary or derived. This idea makes dialogism different from mainstream psychology, which is based on the assumption—self-evident for its adherents—that individuals are there first, and then they sometimes interact with other individuals. Interaction for them is "external," that is, of a secondary nature. Dialogists, by contrast, assume that individuals have become what they are in and through interaction.

Toward a Post-cognitive Educational Paradigm

A related set of attempts to propose contemporary approaches to education, sociology and psychology embody new paradigms of research in keeping with the post-cognitive philosophical paradigm. Some of them are included in Figure 1. They focus methodologically on group interaction and study dynamic processes rather than just pre and post-test learning outcomes of individuals. Most of them are inspired by Vygotsky or, more generally by Marx, Heidegger and Wittgenstein. They include Bruner (1990), Cole (1996), Engeström (1987), Garfinkel (1967) and their colleagues or followers, each of whom emphasizes different aspects of the paradigm.

Vygotsky adopts Marx's ontology: the primary unit of analysis is the interaction among people situated in social relationships and mediated by artifacts. Artifacts are both physically present in the world and meaningful to people (overcoming the physical vs. mental cleavage of Descartes). Vygotsky's notion of artifact includes both tools and language. Their meaning is not projected from individual minds, but is intersubjectively emergent from social interactions, as in the dialectical analyses of Hegel and Marx. Consider Vygotsky's programmatic attempt to show how the individual mind is grounded in activity within the physical and social world. His description of the genesis of the pointing gesture illustrates a typical early experience of meaning for a small child; it shows how the meaning of this artifact (the pointing gesture) is created in the intersubjective world and only subsequently incorporated (internalized) in the child's personal sense-making repertoire:

> We call the internal reconstruction of an external operation *internalization*. A good example of this process may be found in the development of pointing. Initially, this gesture is nothing more than an unsuccessful attempt to grasp something, a movement aimed at a certain object, which designates forthcoming activity…. When the mother comes to the child's aid and realizes this movement indicates something, the situation changes fundamentally. Pointing becomes a gesture for others. The child's unsuccessful attempt engenders a reaction not from the object he seeks but from another person. Consequently, *the primary meaning* of that unsuccessful grasping movement *is established by others*…. The grasping movement changes to the act of pointing. As a result of this change, the movement itself is then physically simplified, and what results is the form of pointing that we may call a true gesture. (Vygotsky, 1930/1978, p. 56, italics added).

Here we see the *genesis of the meaning* of a pointing gesture. The meaning of the pointing gesture is not some mental schema stored in the mind of an interpreting subject, but an intersubjectively understood practice originally generated through interaction and subsequently repeatedly applied during interaction as a resource for maintaining joint attention of group members. The recognized, practical and formalized gesture becomes an artifact: it embodies meaning in the physical world. The meaning is a reference to that which is pointed at. The baby intended some object; the mother recognized that the baby intended that object; the baby recognized that the mother recognized this. The multiple mutual recognition entails that the baby and the mother recognize each other as people who can have intentions and who can recognize intentions of other people. This is a first glimmer of self-consciousness, in which the baby becomes conscious of his own and other people's intentionality. (Of course, the baby cannot represent or express this self-consciousness in any mental, verbal or conceptual sense, but only adopt it behaviorally.)

The key point for us here is not so much the birth of intentionality, social recognition or self-consciousness. It is the analysis of an artifact, such as the pointing gesture, a ubiquitous form of reference or deixis. In the origin of this gesture, we already see the basis for intersubjective, *shared understanding* of an artifact's meaning. The subsequent usage of this pointing gesture is premised upon the mutual recognition of an underlying relationship of shared attention, which emerged within the mother-child interaction.

The view of shared intention as co-constructed in the world stands in sharp contrast to the rationalist assumption that individuals first have private personal intentions—as though produced by logical calculations of self-interest by a homunculus in their heads—which they subsequently express in speech or action. Marx, Wittgenstein and Heidegger—and their successors—soundly reject this cognitive assumption (see, e.g., Dennett, 1991; Dreyfus, 1992; Suchman, 2007). Heidegger (1927/1996), for instance, replaces Descartes' dichotomy of mental and physical with a philosophy of human being-there-together-in-the-world. One's comportment in the world precedes one's reflection upon objects in the world. People understand the shared world through their involvement with and their care for the world with other people who also inhabit that world, not initially through mental representations and logical plans. Human involvement is fundamentally processual or temporal: we aim at our projects for the future, based on having been thrown by our social past into our shared situation in the present.

In their seminal post-cognitive analysis of agency, drawing on contemporary philosophy and social science, Emirbayer and Mische (1998, p. 962) conceptualize agency in Heideggerian temporal terms. Applied to the group unit of analysis as "group agency," their post-cognitive concept could inform CSCL analysis (as in Charles & Shumar, 2009; Damsa, 2014). It is important to reconsider the notion of agency (and causality)—as Latour (1990; 1992) does by extending it to other people and artifacts in networks of actors. The traditional, mechanistic conception of agency contributes to the difficulty of overcoming cognitive habits of thought. A post-cognitive paradigm could include group cognition, collective intentionality and group agency.

The Need for a Post-cognitive CSCL Paradigm

A paradigm shift can be motivated by anomalies in established theories (Kuhn, 1972; Lakatos, 1976). Anomalies are findings that cannot be easily accounted for in a prevailing theory. They suggest the need for a change in theory. Consider two anomalies in the cognitive paradigm of measuring learning outcomes of individual minds: one from the research of Vygotsky and one from recent CSCL research.

In Vygotsky's well-known discussion of the "zone of proximal development," he cites a study in which children "could do only under guidance, in collaboration and in groups at the age of three-to-five years what they could do independently when they reached the age of five-to-seven years" (1930/1978, pp. 86f). CSCL can be seen precisely as such an effort to stimulate students within their zones of proximal development—on tasks they cannot yet master individually but are close to being ready to learn—under guidance, in collaboration and in groups. If the desired results of this do not show up as learning outcomes measurable in individuals (outside of their group context) for several years, then the key effect will be systematically missed by traditional methods of testing individuals. The failure of the cognitive paradigm of instructional research to account for processes in the zone of proximal development—so central to learning—should be considered an anomaly, suggesting the need for a paradigm shift.

In his less quoted section on "Problems of Method," Vygotsky (1930/1978, pp. 58-75) called for a new paradigm of educational research almost a century ago. Arguing that one cannot simply look at visible post-test results of an experiment, he proposed a method of "double stimulation" where a child is confronted by both an object to work on and an artifact to mediate that work. Vygotsky does not call for a controlled experiment that compares learning outcomes with and without the furnished artifact. "The experiment is equally valid," he points out, "if, instead of giving the children artificial means, the experimenter waits until they spontaneously apply some new auxiliary method or symbol that they then incorporate into their operations." Taking this approach in a collaborative setting requires an attention to the children's interaction and the sense making that is involved in creative, unanticipated collaborative accomplishments. It involves understanding the unique trajectories of different *groups*, which cannot be statistically aggregated or sorted into standardized categories. This suggests the need to analyze interaction at the group level, rather than just the individual as the cognitive subject.

Relatedly, a number of CSCL studies have repeatedly documented "productive failure" (Barron, 2003; Kapur & Kinzer, 2009; Pathak, Kim, Jacobson & Zhang, 2011; Schwartz, 1995). This is one of the most intriguing findings of CSCL to date. However, it has so far been analyzed in terms of individual student learning outcomes, rather than group practices within zones of proximal development. When a number of small groups of students work on a challenging problem, the groups sometimes fall into two categories: (a) Groups that fail to solve the immediate problem but excel at solving future related problems. (b) Groups that succeed at solving the immediate problem but are less successful than the first groups at solving subsequent related problems. The robust and repeatable result of these experiments presents an anomaly for traditional educational theory. One could speculate that in the "failure" groups students are further developing their zone of proximal development or that these groups are co-constructing helpful new meanings, whereas the groups that solve the immediate problems are focused on efficiently applying their existing skills. The analysis of group processes effecting outcomes this way would require a post-cognitive perspective, focused on the cognitive accomplishment of the group as such.

A CSCL Researcher's Agenda

As an example of a CSCL research project conducted within a post-cognitive paradigm, I describe my own work during the past decade and a half. It is post-cognitive in that it analyzes the group processes that constitute collaborative learning in a computer-mediated setting. It neither defines learning in terms of outcomes nor interprets utterances in terms of mental phenomena. Without denying the reality of either individual consciousness or societal practices, it nevertheless focuses on the temporal sequentiality of small-group interaction.

The Virtual Math Teams (VMT) Project has been a collaborative effort with researchers from the Math Forum, Drexel University and Rutgers University at Newark, as well as with visiting scientists and colleagues abroad. The project is extensively documented in four books (Stahl, 2006; 2009; 2013c; 2016), nine doctoral dissertations and many other presentations (http://gerrystahl.net/vmt/pubs.html), including in a number of Investigations in this volume.

VMT is a design-based research (DBR) project, intended to develop theory and research methodology through exploring and designing technology and pedagogy for supporting online collaborative learning of mathematics. As a research prototype, the VMT environment has been used in over a thousand student-hours at the Math Forum (http://mathforum.org), as well as independently by researchers in Turkey, Israel, Singapore, Brazil and New Jersey. The final version of VMT's software and curriculum features a collaborative version of GeoGebra (http://geogebra.org), a popular dynamic-mathematics application. The VMT Project converted the GeoGebra app to a multi-user approach, so that actions by one student are synchronously shared with others in the group.

In a typical session, three to five middle-school or high-school students collaborate synchronously online for about an hour. Often, the same group will work on a series of challenging problems during five to ten weekly sessions in an after-school or in-class setting organized by a teacher who has completed the Math Forum's teacher-professional-development program associated with VMT. Students interact through text chat and GeoGebra actions (see Figure 2). A VMT Replayer shows researchers or teachers what everyone in the group saw and allows a viewer to step through an entire session with the controls added across the bottom. In this screenshot, the group is in the midst of constructing a solution to a challenging problem of inscribed polygons, repeatedly used in the VMT Project. (Interestingly, the researchers had not previously seen or thought of the particular solution collaboratively developed by the group in Figure 2.)

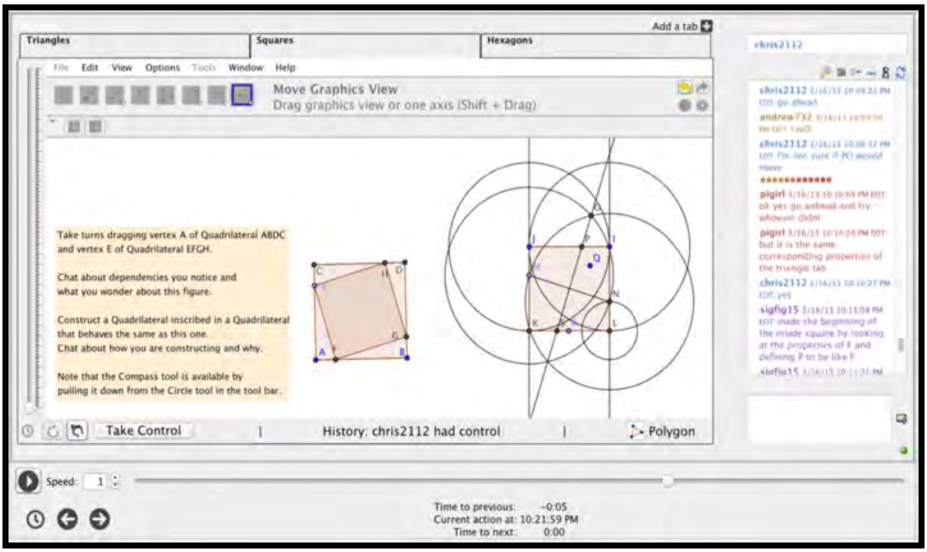

Figure 2. The VMT Replayer, with VCR-type controls below the VMT environment.

The VMT environment is instrumented to provide the data necessary for analysis of group processes. In order to track a group's meaning making, one must have a complete record of all group interaction. Otherwise, one does not know if unrecorded events contributed in unknown ways to the shared understanding. This requirement involves two aspects: (a) controlling the interaction so that no group communication takes place outside of the recorded setting and (b) recording the interaction in a complete, detailed and undistorted manner. Technologies of recording data can make possible new paradigms of research. For instance, conversation analysis only came into existence with the tape-recorder for capturing and replaying speech.

Recording group collaboration in a face-to-face classroom is "messy" and often impractical: There is so much noise that clear speech capture is difficult; transcription is laborious; and non-verbal communication through action and gesture is impossible to capture completely. Traditional analyses generally proceed by coding and counting.

Recordings of speech utterances are transcribed as sentences. Then sentences attributed to the individual speaker are categorized according to some standardized schema. The number of sentences falling into each category is compared for different individuals, groups or experimental conditions. In the process of recording, transcription and aggregation, many researcher interpretations are introduced (Suchman & Trigg, 1991) and any sense of temporal or dialogical process is lost. In particular, given an a priori coding scheme, it is unlikely that any unforeseen and surprising results (like causes of productive failure or creative group moves) will still be identifiable. Due to established methodologies and other research habits, there have been practical barriers to LS making the paradigm shift to studying group interaction. CSCL can overcome these barriers because the computer-mediated collaborative setting makes problem-solving processes observable and automatically fully recordable.

Since students collaborate online in the VMT environment, all communication and action are mediated by the VMT technology. It is therefore possible to capture a complete record of everything that is visible to the student group itself. The same technology is used to replay the session for researchers, who can then slow it down or proceed posting-by-posting and action-by-action, viewing exactly what the students in the group all viewed (as in Figure 2). In addition, a convenient summary log is automatically generated in spreadsheet formats (see Figure 3). The spreadsheet automatically logs all text chat postings and dynamic-geometry actions of each student. It can easily be filtered by event type or re-formatted for log excerpts in publications. Columns for each student give a visual impression of the interactional flow.

	A	B	C	D	E	F	G	H	I	J
1	Line	Date	Start Time	Post Time	Duration	EventType	andrew732	pigirl	sigfig15	chris2112
742		3/16/13		23:49.6	0:00:01	Geogebra:Squares			tool changed to Move Graphics View	
743		3/16/13		23:49.7	0:00:00	Geogebra:Squares			release control	
744	155	3/16/13	23:50.9	23:52.3	0:00:01	chat			it works	
745	156	3/16/13	23:56.7	23:57.3	0:00:00	chat		nice		
746	157	3/16/13	23:54.2	23:58.7	0:00:04	chat	wow, great			
747	158	3/16/13	23:59.3	24:08.1	0:00:08	chat		can you simply explain how you made it		
748	159	3/16/13	24:14.3	24:26.6	0:00:12	chat				If you notice on the example, Length CE is equal to GB
749	160	3/16/13	24:27.6	24:51.3	0:00:23	chat				so you can use to compass tool to make a circle around B with point G on it such that as you move E, G moves correspondingly
750	161	3/16/13	24:53.5	24:59.4	0:00:05	chat				Then make a line going through EG
751	162	3/16/13	24:59.6	25:08.0	0:00:08	chat				and a circle with cenger E point G
752	163	3/16/13	25:08.2	25:13.3	0:00:05	chat				and a circle with cetner G point E
753	164	3/16/13	25:13.5	25:32.7	0:00:19	chat				so that a line perpendicular to EG and through the intercepts of the circles is the midpoint line
754		3/16/13	25:33.5	25:34.3	0:00:00	awareness				[fully erased the chat message]
755	165	3/16/13	25:34.5	25:35.3	0:00:00	chat				of EG
756	166	3/16/13	25:35.5	25:58.1	0:00:22	chat				and whatever points on that line intercept the outside sqaure would then make up the other two points of the inner square
757	167	3/16/13	26:03.4	26:05.8	0:00:02	chat			okay good	
758	168	3/16/13	26:34.4	26:36.5	0:00:02	chat		that makes sense		
759	169	3/16/13		26:55.2	0:00:18	system			Now viewing tab Hexagons	
760	170	3/16/13	26:49.0	26:55.6	0:00:06	chat		can we move to "hexagons"?		
761	171	3/16/13		27:00.0	0:00:04	system				Now viewing tab Hexagons
762	172	3/16/13		27:06.4	0:00:06	system		Now viewing tab Hexagons		
763	173	3/16/13		27:46.6	0:00:40	system	Now viewing tab Hexagons			
764	174	3/16/13	27:57.8	27:59.8	0:00:01	chat			ill drag	
765		3/16/13		28:02.2	0:00:02	Geogebra:Hexagons			take control	
766		3/16/13		28:02.3	0:00:00	Geogebra:Hexagons			tool changed to Move	
767		3/16/13		28:10.3	0:00:08	Geogebra:Hexagons			updated Point A	
768		3/16/13		28:30.6	0:00:20	Geogebra:Hexagons			updated Point G	
769		3/16/13		28:32.3	0:00:01	Geogebra:Hexagons			tool changed to Move Graphics View	

Figure 3. A spreadsheet of a segment of VMT interaction among four students.

The text chat is reproduced just as posted by the students, and the GeoGebra actions are listed in detail. The data of the actual interaction is available, and the process of interpretation begins with the analysis, not with the data capture and transcription. Researchers can share the replayer files and spreadsheets, so that others can check any analytic descriptions for plausibility.

The VMT system's ability to generate data, which (a) provides an automatic record of the actual interaction and (b) documents the complete group interaction, has made it useful to a number of researchers. Using this data source, they have been able to analyze group processes, rather than just individual actions or outcomes. Here are some examples of theoretical insights and methodological innovations emerging from the VMT Project before the integration of GeoGebra, when a generic shared whiteboard was used for mathematical figures:

Sarmiento and Stahl (2008) extended the notion by Teasley and Roschelle (1993) of a Joint Problem Space, observing how students co-construct such a shared conceptualization and how it incorporates a temporal structure, integrating past collaborative sense-making results into current discussions aimed at a projected future problem solution.

Çakir, Zemel and Stahl (2009) [Investigation 12] observed how a student group integrated their visual/graphical reasoning, numeric/symbolic expression and mathematical discourse in their problem-solving work within the VMT chat and whiteboard media—moving successively from one discourse to another.

Zhou, Zemel and Stahl (2008) looked at the important role of questioning as a common driving force in collaborative interaction, eliciting responses and providing a guiding group agency.

Zemel, Çakir and Stahl (2009) analyzed "reading's work" as a contribution to the analog of conversational turn taking as it is materialized in online text chat.

Zemel and Koschmann (2013) [Investigation 5] studied how deixis and linguistic reference work within interactions in the VMT environment.

Koschmann, Stahl and Zemel (2009) examined the nature of several key group practices in VMT collaboration.

Wee and Looi (2009) investigated pivotal moments in group processes of mathematical knowledge building in VMT chats.

Medina and Suthers (2013); Medina, Suthers and Vatrapu (2009) probed the nature of representational practices in a series of one VMT group's sessions, observing how practices primarily contributed by one student are later associated with the other students, as they become adopted as group practices.

Trausan-Matu, Dascalu and Rebedea (2014) analyzed the polyphonic nature of VMT chats, graphing the intertwining of dialogical voices in a number of groups.

More generally, the concept of group cognition emerged from the early analyses of the VMT Project, as did the importance of interaction analysis (Stahl, 2006). In turn, the theory of group cognition clarified the importance of incorporating a domain-oriented shared workspace like GeoGebra and the need to record all interaction for analysis. These issues were reflected upon in (Stahl, 2009). The co-evolution of theory, research and design characteristic of design-based research (DBR) was highlighted in (Stahl, 2013c), with chapters on eleven aspects of the Project, including theory, methodology, pedagogy, technology, subject domain, history and philosophy.

The idea of focusing on the group unit of analysis or group cognition does not exclude analyses at either the individual or the community units of analysis. There are important and different phenomena and processes at each of these (and other) levels. In fact, it is often most fruitful to analyze cognition on multiple levels and to see how the processes at the different levels work together. However, the simultaneous and integrated study across levels is a current challenge for CSCL [Investigation 2]. A variety of *interactional resources* are typically at work bridging the levels (Stahl, 2013a; 2013b; Stahl & Öner, 2013). Since incorporating GeoGebra into VMT, our research has included designing sequences of curricular resources to guide collaborative exploration and bridge levels by tying individual and group knowledge to established knowledge of the mathematics community (Stahl, 2012; 2015).

In VMT case studies, topics in mathematical combinatorics or dynamic geometry centrally figure as interactional resources that bring together individual, small-group and community cognitive processes. *Sequentiality*, *co-attention* and *shared understanding* have emerged from these studies as fundamental theoretical categories for understanding and studying collaborative learning [Investigation 19]. By observing group interaction in VMT, we can see how student groups enact these mechanisms and thereby integrate individuals into groups, adopting community practices as *group practices*. For instance:

In (Stahl, 2011) [Investigation 23], two students solve a high-school math problem that has stumped them for some time. The problem-solving steps that the dyad goes through as a team are strikingly analogous to how proficient math students solve problems individually. In the discourse captured in this case, one can see how the *group* integrates contributions from the two *individual* participants to accomplish a task in accordance with *community* standards of practice—illustrating the productive interplay of cognitive levels. A sequence of ten discourse moves (similar to extended adjacency pairs in Schegloff, 2007) by the group details their *sequential organization* of the problem [Investigations 23 and 25].

In (Stahl, Zhou, Çakir & Sarmiento-Klapper, 2011) [Investigation 17], three students develop techniques for helping each other to see what they are seeing in the diagram they have drawn for a math problem. This *persistent co-attention* to a shared object of analysis allows the team to solve their problem as a group.

Similarly, in (Çakir & Stahl, 2013) the students are able to work together because they effectively manage their *shared understanding* of the problem.

(Stahl, 2016) follows a group of three young girls longitudinally through eight hour-long sessions in the VMT chat room with a multi-user version of GeoGebra. It describes the display of mathematical reasoning by the team discussing the dependencies of a series of dynamic-geometry figures. By analyzing the network of mutual responses, it tracks the intersubjective meaning-making process and observes how the team develops its abilities by adopting *group practices* of collaboration, mathematical discourse and dynamic geometry.

When a group enters the VMT environment, it is presented with a challenging math problem, which is designed to guide the group interaction in an academically productive direction [Investigation 21]. The problem acts as a problem-solving resource for the group. The group must interpret the problem statement, elaborate the way in which they want to conceive the problem and determine how to proceed [Investigation 5].

A math problem, for instance, can serve as an effective interactional resource for bridging across cognitive levels. Typically, it introduces content—definitions, elements, procedures, principles, practices, proposals, theorems, questions—from the *cultural* traditions of mathematics and from school curriculum. In so doing, it recalls or stimulates *individual* cognitive responses—memories, skills, knowledge, calculations, deductions. It is then up to the *group* interaction to bring these together, to organize the individual contributions as they unfold in the on-going interaction in order to achieve the goals called for by the community, institutional, disciplinary and historical sources. In this way, the group interaction may play a central role in the multi-level cognition, interpreting, enacting and integrating elements from the other levels, producing a unified cognitive result and thereby providing a model for future community practice or individual skill.

Group cognition is not the same as individual cognition. Certainly, it relies upon individual cognition to make essential contributions; however, one cannot say that all of the cognition is reducible to the individual unit, because the work of assembling the high-level argumentative structure typically occurs at the group unit of analysis. Surely, putting together problem-solving arguments (incorporating planning, synthesis, deduction) must be considered a cognitive activity as much as the memory or computation that goes into making the detailed contributions to individual steps. This group cognition may be considered to involve students in their zone of proximal development, with the expectation that they may later be able to conduct such extended problem-solving argumentation individually, based on their group experiences.

In addition, the individual discourse contributions are not meaningfully separable from the group processes. They are largely responses to what has gone before in the group interaction. These contributions are expressions that would not have occurred without the preceding opening for them and the elicitation of them by the group process. Many of the contributions are largely reactions at the group level, which reference and inter-relate resources available in the discourse context more than they introduce new elements from the personal perspective and individual background of the actor. They are also prompts for reactions by others. The important knowledge-building achievement is emergent in this give-and-take at the group level, rather than a simple collection of expressions of isolated individual cognitive accomplishments.

Note that the emergence of group cognition is quite different from the emergence of complexity from the non-linear interaction of simple rules in chaos theory; group cognition emerges primarily through the intertwining of subtle linguistic phenomena of indexicality and sedimented shared meaning inherent in sequentially organized utterances of multiple voices [Investigation 2].

Of course, coherent and impressive examples of group cognition—such as solving a math problem that the group members would not have been able to solve on their own—do not occur every time that people come together in conversation. In fact, the research field of CSCL has repeatedly documented that desirable forms of collaborative knowledge building are disappointingly rare. The VMT research summarized above indicates some reasons for this. First, it is difficult to set up a group interaction where everything relevant to the cognition at the group level of analysis is captured in a form adequate for detailed analysis. It took years to iteratively design, develop and deploy the VMT group sessions to successfully generate adequate data of successful group cognition. Secondly, the group interaction must be directed and guided to focus on an appropriate cognitive task. Certain challenging math problems, carefully presented, seem to provide effective interactional resources for stimulating interesting episodes of group cognition. Additionally, groups must work consistently to ensure the presence of certain preconditions of effective group cognition. They must persist in building *longer sequences* of responses to each other, they must maintain continuous *co-attention* to a shared focus of discussion, and they must build and sustain a *shared understanding* of the topic of conversation [Investigation 19, Investigation 23].

The VMT studies listed above are focused on the small-group unit of analysis. This is consistent with other contemporary attempts to shift away from an exclusive concern with individual cognition, for instance in actor-network theory, ethnomethodology, distributed cognition and activity theory. In the VMT project, most analysis has focused on the under-researched unit of the small group (Stahl, 2006; 2009). However, recent work on VMT looks at the interactions among the individual, small-group and community units of analysis (Stahl, 2013a; 2013c). This has the potential of bridging to other analytic approaches in LS and CSCL, although it raises new methodological issues about studying the interrelationships of the different levels.

The Foundational Relationship of CSCL to the Learning Sciences

The post-cognitive educational paradigm assigns an analytic priority to group cognition, as the level at which fundamental processes of learning take place. Applying this to the study of learning is motivated by Vygotsky's developmental principle:

> Every function in the child's cultural development appears twice: first, on the social level, and later, on the individual level; first, between people (*interpsychological*), and then *inside* the child (*intrapsychological*). This applies equally to voluntary attention, to logical memory and to the formation of concepts. All the higher [human mental] functions originate as actual relations [interactions] between human individuals. (Vygotsky, 1930/1978, p. 57)

Cognitive phenomena such as specific forms of learning develop first in group interaction and then only subsequently—through complex and extended transformations—emerge as individual skills or outcomes. In this sense, collaborative learning may be considered not just an optional and rare mode of instruction, but rather a foundation of all learning. Group cognition is a basis of human cognition: individual, small-group and community.

Already in the Introduction to *Group Cognition*, it was proposed that:

> Small groups are the engines of knowledge building. The knowing that groups build up in manifold forms is what becomes internalized by their members as individual learning and externalized in their communities as certifiable knowledge. At least, that is a central premise of this book. (Stahl, 2006, p.16)

Accordingly, the analysis of group processes is foundational for the study of learning because these processes mediate between individual and community learning. One can argue, as Vygotsky and his followers often do, that group cognition underlies and grounds all cognition. Human thinking—including planning, conceptualizing, narrating, analyzing and problem solving—involves language to identify, distinguish and express itself. Vygotsky studied the development of children's thinking and speaking, concluding that spoken language (learned in dialog within family groupings) gradually over years led to silent self-talk, which then eventually morphed into mental thought. Accordingly, thinking individuals evolved (both as a species and in each case) from group participants, adopting as their own many practices that were acquired in interaction with others. While it is difficult to know about the early origins of cognition, the priority of group cognition seems apparent in the kinds of learning targeted by most CSCL research projects.

While the existence of many small groups may be ephemeral and teams may form for limited time spans, groups are typically the units within which cognitive advances are made, particularly the kinds of challenging, ill-structured, complex forms of learning aimed at by CSCL interventions. For instance, the collaborative learning of dynamic geometry by the Cereal Team and the solving of tricky problems of mathematical combinatorics by other VMT student groups were cognitive accomplishments that the individual team members often would not have been able to achieve on their own. The analysis of their interaction documented that the individuals ended up with deeper understandings as a result of their participation in the team's collaborative learning.

Other CSCL projects explore similar results in fields of scientific conceptualization, ecological interdependencies or argumentation about controversial social issues. In such realms of learning, the challenge is beyond the ability of most individual students, but can be approached with well-designed CSCL resources, tools and supports, as well as the interaction of multiple student perspectives and skills. Experiences of collaborative learning can direct the cognition of participants as well as provide models of reflection for subsequent individual thinking.

For a different kind of example, consider how knowledge building took place within the communities of CSCL and LS themselves, as illustrated in the discussion of their history at the start of this Investigation. A sociocultural description of how they changed might argue that individual researchers apprenticed to the research communities and gradually adopted the prevalent social practices of data analysis and publication (Lave & Wenger, 1991). As the researchers innovated, the communities were modified in turn. However, theories at the level of the individual and the community run into the problem of structuration (Giddens, 1984)—how these two levels influence and respond to each other. If one considers what took place at the CSCL 2003 conference, one sees that community-level institutions like ISLS and *ijCSCL* were structured through processes of group interaction. There were tensions between political groupings representing different constituencies, and each of these groupings engaged in internal and external interaction. Ad hoc groups sprung up and committees were established to define the community structures. As people interacted within small groups in this context, they changed their individual identities and modified social practices of their field. Through such mechanisms, the group processes mediated and transformed both the individual and community processes, helping to define individuals' identities and institutional practices. In this sense, as the engines of structuration, the group unit of analysis is foundational for the study of change and learning at multiple levels.

The group cognition paradigm argues for scientific study at the small-group unit of analysis (Stahl, 2010) in addition to the individual and community units. Too often, traditional educational researchers reduce group-level phenomena either to individual-psychological constructs or to societal institutions and practices. But, as we have documented in VMT case studies, there are often important practices and processes taking place at the small-group unit of analysis that are not reducible to the mental behaviors of an individual or to the institutions or established practices of a community.

The term "group cognition" does not mean there is some kind of "group mind" at work or anything other than the interaction of the students in a group. Rather, it means that the analysis of cognitive achievements may be most appropriately conducted at the group unit of analysis—in the VMT context, in terms of the collaboration recorded in the interplay of the text-posting and geometric-drawing actions shared by the group.

For instance, a specific student utterance or text posting is not to be ascribed to hypothesized mental processes of the student (what one assumes the student may be thinking, feeling or trying to accomplish). Rather, it is taken as a situated response to what came before (such as actions or utterances by other students) and as an invitation to subsequent group action [Investigation 23]. That is, it is analyzed as a dialogical move situated in ongoing group interaction. Methodologically, a study of group cognition aims to understand interactional responses within the group rather than cognitive motives of individuals' actions.

CSCL could fully embrace the group cognition paradigm, as illustrated in the VMT Project. This would be appropriate since CSCL was created in response to the potential of networked computers to bring people together into functional groups to collaborate. More specifically, CSCL is oriented to the potential of bringing students together to learn collaboratively. This effort should focus on the group-level interactions in which problem solving, knowledge building and other forms of collaborative learning take place.

CSCL is not the science of some existing, objectively observable phenomenon, like physics or psychometrics are often assumed to be. It is the search for a new form of learning—taking advantage of technologies that are yet to be developed and group processes that are difficult to observe and have largely gone unnoticed. Therefore, it cannot be studied in the manner of a summative assessment, by comparing measurable learning outcomes. It is more of a design science, using design-based research to transform "existing situations into preferred ones" (Simon, 1981). In DBR, the vision of CSCL itself is a product of research.

To guide redesign in iterative research projects, it is not sufficient to "predict" the percentage increase in outcomes that is attributable to a particular, currently available technological condition. What is needed is insight into how groups of students in realistic situations may actually make sense of and take advantage of possible technologies, as well as what barriers groups may encounter in trying to use them. This means looking at how groups of students actually interact with various technological artifacts and observing their intersubjective meaning-making processes, their enacting of the technologies and their collaborative problem solving as mediated by the technologies.

Of course, not all groups of students will act the same way under similar conditions. Groups are unique—with students at different zones of proximal development for different skills and with interactions highly situated within un-reproducible discourse trajectories. Therefore, statistical generalization is not a relevant goal in such research. What one seeks, rather, is a detailed understanding of the practices that are actually found to be at work in observed cases [Investigation 16].

According to ethnomethodology, communities necessarily use shared practices or member methods (Garfinkel & Sacks, 1970). Otherwise, intersubjective sense making would not be possible—any more than communication would without a common language. Therefore, the practices that one observes in a single case may be representative of widely used practices. Researchers familiar with a domain—such as experienced math educators—can often tell what seems like a typical group behavior within that educational arena.

LS and CSCL have made significant progress in recent decades, as documented by (Evans, Packer & Sawyer, 2016; Sawyer, 2014). However, it may be timely to pursue a new research paradigm explicitly—one in which CSCL plays a foundational role. For the CSCL and LS research communities to make the major paradigm shift advocated here will involve significant re-tooling and adoption of new methods. It will also require increased collaboration with colleagues in social science who are more familiar with analyzing interaction and language and with formulating rigorous descriptive accounts of group-interactional processes. Fortunately, the requisite technological recording capabilities are available and the evocative research questions are at hand.

The settings studied by LS and CSCL today are complex. Many diverse studies can contribute to an understanding of the learning taking place. Such studies can pose a broad spectrum of research questions, each with its own theoretical framing and methodological approach. Certainly, traditional quantitative and qualitative analyses at the individual unit of analysis can provide important parts of the picture, as can considerations of social practices and community participation. However, it is also necessary to consider the temporal processes of group interaction, through which the individual and the community are often mediated and through which learning takes place as a process, not just as an outcome.

Too often, CSCL is treated as a secondary niche within LS. This is probably because commonsensical attitudes assume that individual learning is the primary goal, and that collaborative learning is just one of many possible approaches. However, if one understands that individual learning is actually secondary and dependent upon group cognition, then CSCL should be viewed as foundational to human learning.

In his reconsideration of the CSCL paradigm, Koschmann (2001, p. 21) concluded that "we have yet to develop a consensus within the CSCL community with regard to what it means to learn and how to study the process." I have argued here that a paradigm-shaping research question for LS would *treat learning as essentially an intersubjective, interactional process*, and would *study it by investigating the dynamic developmental processes through which individual, small-group and community cognitive practices emerge.*

Within CSCL, the seminal analysis by Teasley and Roschelle (1993) pursued a specific version of this question by asking how dyads of students created a joint problem space around a computer representation of velocity and acceleration. The VMT Project followed a different approach to the same question by exploring how students co-construct interactional, group-cognitive and mathematical practices in small online groups mediated by collaborative-dynamic-geometry tasks and tools (Stahl, 2013c; 2016). Taking approaches like these, research in a post-cognitive CSCL paradigm could lead research in LS by working out the interactional foundations of all learning through taking advantage of technologies, pedagogies and understandings afforded by CSCL.

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10. Practices in Group Cognition

Abstract. The analysis of *group practices* can make visible the work of novices learning how to inquire in science or mathematics. These ubiquitous practices are invisibly taken for granted by adults, but can be observed and rigorously studied in adequate traces of online collaborative learning. Such an approach contrasts with traditional pre/post comparisons that miss sequential interactional processes or that reduce group phenomena to individual or social factors. The analysis of the enactment of practices by small groups in CSCL contexts can systematically inform the design, testing and refinement of collaborative-learning software, curriculum, pedagogy and theory. The research of the Virtual Math Teams Project resulted in a new way of viewing collaborative learning. According to this view, CSCL can be re-conceptualized as the design of technology to foster the adoption of group practices by student teams.

Keywords. Group practice, CSCL theory, CSCL methodology, design-based research

A new method for CSCL

As a CSCL researcher, participant in all previous CSCL conferences and former Editor of *ijCSCL*, I have consistently observed that almost all published studies of collaborative learning reduce it either to individual mental representations or to cultural social practices; the small-group unit of analysis is under-researched (Stahl, 2006a). This may be partially because it is difficult to find data that adequately documents collaborative learning by reliably capturing all the discourse, gestures and artifacts that enter into *group* (i.e., small-group, collaborative) knowledge-building processes (Stahl, 2013a). Furthermore, the methods of traditional educational-psychology research are inadequate for investigating many core CSCL issues because they focus on individual cognition and assume that utterances can be categorized objectively (i.e., without interpretation based on understanding the sequential meaning-making) (Stahl, 2014). My conclusions are controversial within the CSCL research community because they methodologically eschew prevalent cognitivist and positivist assumptions associated with methodological individualism (Stahl, 2016b).

Throughout the history of CSCL as a research community, the methodological tension of the field has been informally described as an opposition of "quantitative" versus "qualitative" approaches (Jeong, Hmelo-Silver & Yu, 2014; Suthers, Dwyer, Medina & Vatrapu, 2010). Habermas refines this with the epistemological distinction between calculative and sense-making orientations, which pervades modern science (Hammond, 2015). Sfard (1998) saw the contrast as (individual) acquisition versus (cultural) participation. Viewed in terms of the unit of analysis, "socio-cognitive" psychology focuses on representations in individual minds and "socio-cultural" anthropology centers on socially defined practices. In other words, there has been no methodological focus on the small-group unit of analysis—precisely where one would naturally expect to observe collaborative learning in CSCL (Stahl, 2009). Some psychologists recognize that individual learning can be influenced by groups (Cress, 2008) and some sociologists show how social practices are enacted and maintained in group interaction (Garfinkel, 1967; Giddens, 1984). However, as noted by Schwarz and Baker (2017), even these studies rarely analyze empirical data of collaborative learning in ways that display processes of small groups building knowledge or acquiring practices.

Quantitative and qualitative methods are appropriate for measuring net changes due to hypothesized independent variables. However, CSCL needs ways to analyze the group processes that bring about such changes and that establish group practices—in order to guide iterative design-based research (DBR). To not only judge the statistical effectiveness of CSCL interventions in promoting collaborative learning, but also to identify specific problems and to suggest innovative functionality during DBR cycles, it is necessary to analyze, understand and theoretically conceptualize temporal group processes as such, in their sequential unfolding (Stahl, 2013b). Moreover—as anyone knows who has successfully implemented CSCL in classrooms or created effective technological support for it—many cycles of trial and refinement of approach as well as of technology design are necessary to develop effective CSCL pedagogy and tools: DBR as an integration of theory, design, research and practice.

Traditional methods provide evidence *that* change has taken place (between a pre and a post state), without describing *how* the change took place, beyond speculation based on assumptions from folk theories of cognition (Stahl, 2016b). For instance, groundbreaking CSCL studies (Kapur & Kinzer, 2009; Scardamalia & Bereiter, 2014; Schwartz, 1995) indicated that important learning took place at the group level, without being able to show how it happened. A number of researchers have proposed that unique cognitive processes take place at the small-group level (Barron, 2003; Dillenbourg, Baker, Blaye & O'Malley, 1996; Hutchins, 1996; Rogoff, 1995), but they have not collected the required data for a systematic analysis at the group unit.

Sfard (2008) argued that learning math is a matter of acquiring many *practices* that are passed down in the culture of mathematics. Vygotsky laid the basis for collaborative-learning theory by proclaiming that practices are acquired socially (e.g., in dyads or small groups) first, and subsequently adopted by individuals. This notion of practices—when applied at the group unit of analysis—provides a way of conceptualizing regularities of group-cognitive processes. My colleagues and I set out to generate and analyze CSCL interactions in which we could observe such small-group practices emerging.

Studies of group practices

In 2002, we initiated the Virtual Math Teams (VMT) research project at the Math Forum. We gradually developed a prototypical CSCL DBR project, which investigated mathematical education with small teams of students in a custom online collaboration environment. The VMT software was instrumented to collect comprehensive interaction data and to provide it to researchers in useful formats. Later, we developed and incorporated a multi-user version of GeoGebra to provide computer support more specifically for dynamic-geometry math content.

My published books draw successive lessons from the phases of this research: *Group Cognition* (Stahl, 2006a) proposes analyzing knowledge-building phenomenon at the small-group unit of analysis. *Studying VMT* (Stahl, 2009) describes our scientific approaches to supporting and analyzing small-group problem solving in the VMT context. *Translating Euclid* (Stahl, 2013b) discusses the many facets of DBR for supporting constructionist CSCL using VMT.

Finally, *Constructing Dynamic Triangles Together* (Stahl, 2016a) follows utterance-by-utterance a team of students developing mathematical understanding through an eight-hour longitudinal case study, as the group progressively masters collaborative online dynamic geometry. It identifies about sixty "group practices" that the team explicitly, observably enacts. We found that these practices successively contribute to various core aspects of the group's abilities: to collaborate online; to drag, construct and transform dynamic-geometry figures; to use GeoGebra's software tools; to identify and construct geometric dependencies; and to engage in mathematical discourse about their accomplishments.

The notion of *group practices*, as it emerged in this research, provides a foundation for a new way of viewing, analyzing, theorizing and supporting CSCL. Group practices mediate between individual cognition and community culture (Stahl, 2006a, p. 16; 2013b, ch. 8). They can be observed and analyzed in small-group interactions. Thereby, the theory of group practice provides a research-based solution to the obstinate issues of meaning making, intersubjectivity, structuration and connecting levels of learning (Giddens, 1984; Stahl, 2012b; 2016a), while focusing analysis on the small-group unit, as central to collaborative learning. Intersubjective meaning making and knowledge sharing take place via group practices like turn taking, pointing, questioning and drawing. Individuals can transform the group practices into personal skills and mental abilities. Practices can also pass back and forth between small-group and classroom or cultural levels.

The group practices identified in VMT studies are all based on captured interaction data. These practices arose in observable breakdowns or interactional difficulties and were each enacted explicitly in student discourse. Ethnomethodologically speaking, the practices are observably issues for the participants themselves (Stahl, 2012a). They can be identified through close analysis of discourse and other forms of interaction, such as geometric sketching or pointing within the online VMT environment.

The identification of group practices has substantial implications for the design of CSCL software, curriculum, scripting, pedagogy and experimental interventions. In DBR, one develops an initial prototype environment and tries it out with groups of students. Based on observation of problems, the prototype is iteratively re-designed and refined. By observing breakdowns in group interaction and the gradual enactment of new group practices in response to the breakdowns, a designer can identify problem areas and constructive processes that need additional support. The analysis of group practices provides a systematic analysis method for driving CSCL design—something that has long been lacking in CSCL (Tim Koschmann, Marlene Scardamalia, personal communications).

Although DBR is a popular approach to the development of educational software, especially in CSCL, there is little agreement on how to evaluate trials in a way that contributes systematically to re-design. The theory of group cognition proposed that one could make collaborative learning—or group cognition—visible (Stahl, 2006a, Ch. 18), based on the principles of ethnomethodological description (Garfinkel, 1967). This is because meaning making is an intersubjective or small-group process, requiring group members to make their contributions visible to each other, and therefore also to researchers (Stahl, 2006a, Ch. 16). As the editor's introduction to an important book on ethnomethodology (Garfinkel, 2002) explains, "the sounds and movements that comprise social action are meaningful creations that get their meaning from the shared social contexts of expectation within which they are enacted…. Intended meanings, however, can only be shared if they can be successfully displayed before others in expected ways" (p.57).

This Investigation's analyses of the meaning-making process focus on the sequential response structure (or "adjacency pairs") of utterances, which build on previous utterances and elicit further possible, anticipated or expected responses—in keeping with the approach of conversation analysis (Schegloff, 2007). The analysis re-constructs the web of situated semantic references: "The meaning of the interaction is co-constructed through the building of a web of contributions and consists in the implicit network of references" (Stahl, 2009, p. 523). The analysis of this discourse data makes visible how small groups negotiate and adopt group practices.

The structure of group discourse

Note that meaning is constructed by more than one individual through the elicitation-response pair. That is why interaction analysis is considered to take place at the small-group unit of analysis. If one attributed the meaning of a single utterance to the mental state of the individual making the utterance, then that would be an analysis at the individual unit—and would imply some form of access to the individual's mental state. Single utterances can rarely be adequately interpreted in isolation; they typically include indexical elements that reference prior utterances and other elements of the interactional situation (Zemel & Koschmann, 2013) [Investigation 5]. Therefore, they must be analyzed in terms of their sequential position with respect to utterances of other people.

Most published sequential analyses of conversation are limited to brief excerpts; this Investigation's analysis of hour-long sessions—especially considered within the larger context of the VMT Project—goes beyond the analysis of even so-called "longer sequences" (Stahl, 2011) [Investigation 23]. Analysis of longer sequences is more important in studying geometry instruction than in most conversation analysis. While ethnomethodologically informed conversation analysis (Garfinkel, 1967; Goodwin & Heritage, 1990; Sacks, 1965/1995; Schegloff, 2007) is interested in how meaning is socially constructed in the momentary interaction, we go beyond the ethnomethodological focus. We are here concerned with both (a) longer chains of meaning making and (b) how the meaning-making process itself changes as the group learns to collaborate and to engage in mathematical discourse.

(a) Perhaps geometry's greatest contribution to the development of human cognition was to systematize the building of *chains of reasoning*—presented as deductive proofs or specially structured constructions of graphical figures (Latour, 2008; Netz, 1999). Euclid's proofs could extend to over forty steps, each specified in a prescribed technical language and accompanied by a diagram representing a correspondingly complicated construction. The cognitive capacity to follow—let alone to invent—such a sequence of deduction or construction required the development of meta-cognitive planning and agentic regulation skills (Charles & Shumar, 2009; Emirbayer & Mische, 1998; Stahl, 2005). These skills have since the time of the early Greek geometers become ubiquitous in literate modern society (Ong, 1998). They underlie our scientific worldview and technological lifestyle. Sophisticated planning skills have become second nature (Adorno & Horkheimer, 1945) to us, and we now assume that people are born with rational skills of planning and arguing. It has taken seminal studies of philosophy (Heidegger, 1927/1996) and psychology (Suchman, 2007) to dispel the common rationalist assumption (Dreyfus, 1992) that our actions are the result of previous mental planning, rather than that reasoning is generally posterior rationalization (Stahl, 2013b, Ch. 3), and that we must learn how to make up these explanations after our actions as little retroactive stories (Bruner, 1990), in order to understand and justify them. We would like to see how young, novice teams could develop such sequential reasoning skills, guided by experiences involving geometric construction, analysis and planning. We hypothesize that studying geometry can be an occasion during which significant steps of learning about deductive reasoning can take place. We look at transcripts of discourse and interaction by virtual math teams for the adoption of group practices that involve group agency of sequences of task steps.

(b) Following a chain of development of group agency over time involves the longitudinal analysis of longer sequences of interaction or comparison of excerpts at different points in a temporally extended learning process. Analysis of a single moment can reveal how participants take their activity as instructional or can display signs of having learned something new (Koschmann & Zemel, 2006; Zemel, Çakir, Stahl & Zhou, 2009). However, it can be more informative to compare and contrast interactions at different times to reveal how groups and their participants have taken up previous experiences in current interaction (Sarmiento & Stahl, 2008) and *how that makes a difference to their current meaning making*.

We would like to observe the evolution of group practices and individual skills or understandings over time. Our analytic goal can be called a "learning trajectory." Such a learning trajectory has been characterized as follows:

> A researcher-conjectured, empirically supported description of the ordered network of constructs a student encounters through instruction (i.e., activities, tasks, tools, forms of interaction and methods of evaluation), in order to move from informal ideas, through successive refinements of representation, articulation and reflection, towards increasingly complex concepts over time. (Confrey et al., 2009, p. 346)

Note the central role of instruction here. Instruction is conceived here as the provision of a carefully designed learning environment. As Lehrer and Schauble (2012) put it, "The benchmarks of learning tend not to emerge unless someone carefully engineers and sustains the conditions that support them" (p. 705). Particularly in our study of the Cereal Team (see case studies 3 and 4, below) we analyze how the VMT environment guides the student team's learning trajectory as they adopt group practices that enable them to refine their representations, articulations and reflections over time.

Theory of group practices

Our focus on *group practices* as foundational to collaborative learning is in keeping with the "practice turn" in contemporary social theory and epistemology (Schatzki, Knorr

Cetina & Savigny, 2001). According to Reckwitz (2002), a practice is "a routinized type of behavior which consists of several elements, interconnected to one another: forms of bodily activities, forms of mental activities, 'things' and their use, a background knowledge in the form of understanding, know-how, states of emotion and motivational knowledge" (p. 249). Social practices form our background, tacit knowledge as proposed by twenty-first-century philosophy (Stahl, 2016b) as an alternative to eighteenth-century rationalist (Descartes, 1633/1999) and cognitivist (Kant, 1787/1999) philosophies [Investigation 15].

Practice theory was propounded by Bourdieu (1972/1995). He uses the term "habitus" for our systems of durable, transposable dispositions—or organization of conventionalized, routinized, objectified and embodied habits. As with other concepts, I construe practices primarily at the small-group unit of analysis, rather than as habits of individual bodies or cultural conventions of whole communities—in contrast to Bourdieu and his followers. Group practices are what make collaboration possible: "The homogeneity of habitus is what—within the limits of the group of agents possessing the schemes (of production and interpretation) implied in their production—causes practices and works to be immediately intelligible and foreseeable, and hence taken for granted" (Bourdieu, 1972/1995, p. 80).

Only because group members share the ability to use the same group practices, can the members understand each other's actions and their references to those actions. The intersubjectivity of the group is based on this shared meaning [Investigation 18]. The sharing of meaning is a product of the group interaction that adopts the practice; it is produced in the interaction as the members construct the meaning together (Stahl, 2015b). Group practices are proposed—whether verbally or in action—and then discussed, negotiated, accepted, put into regularized practice, generalized across instances of practice and incorporated into the group's habitus. Then we may say that the group—and often its members—has learned. The analysis of group practices provides a vital key to theorizing, supporting, analyzing and facilitating computer-supported collaborative learning.

Collaborative learning certainly involves individual cognition and socio-cultural influences. Resources from the individual and cultural levels are necessarily introduced into the group interaction, made sense of, negotiated, shared and adopted through small-group processes. The adoption of group practices *mediates* the multiple levels involved in learning (Stahl, 2013a; 2013b). The analysis of group practices provides a powerful new method to study CSCL. By automatically capturing the complete interaction within inquiring online groups of students, CSCL research has the potential to observe and analyze the subtle development and use of group practices for the first time.

Enacting group practices

In analyses of VMT interactions, group practices largely account for the group's teamwork and for its ability to construct knowledge or problem solve as a group. The enacting of cultural or community practices as their own group practices—facilitated by teachers, texts, scripts, interactional resources and knowledge artifacts—is how small groups acquire skills from their social context and how the group participants exchange and appropriate each other's perspectives and skills as individual learning (Stahl, 2013b, ch. 8). *The answer to the question of how the group learns is that it successively adopts various practices and incorporates them in its on-going interaction.* As Vygotsky (1930/1978) proposed, such small-group learning generally precedes learning by "isolated individuals" (still surrounded by texts, motivations, and objectives from family members, workplace colleagues, classroom friends and other small groups).

As observed in our studies, the adoption process often follows a general pattern (Stahl, 2016a):

- First, the group encounters a "breakdown" situation in which they do not know what to do.
- Then someone makes a proposal for action. There may have been a preceding series of proposals, some ignored or failed (see Stahl, 2006a, ch. 21) and others rejected by the group.
- The proposal may be followed by a negotiation process as group members question, refine or amend the original proposal through secondary proposals.
- Finally, there is often an explicit round of agreement.
- Perhaps most importantly, the new practice is put to work in overcoming the breakdown situation.
- In the future, the practice may be simply applied without discussion. Of course, there could also be instances of backsliding, in which the group fails to apply a previously adopted practice where it could help.

This general pattern is not a rational model of mental decision-making. Rather, it involves tacit behavior, where a breakdown leads to explicit knowledge, followed by negotiation and eventually a return to tacit practices (Stahl, 1993, ch. 4). The adoption process is driven by interpersonal interaction engaged in the world, not by logical deductions in individual minds.

The catalog of group practices compiled from analysis of VMT data agrees well with lists of social practices enumerated in the literature (Stahl, 2016a). For instance, we identified online versions of practices defined by face-to-face conversation analysis: sequential organization (response structure), turn taking, repair, opening and closing topics, indexicality, deixis, linguistic reference and recipient design (Zemel, Çakir & Stahl, 2009). Other group practices correspond to practices CSCL has previously investigated: joint problem spaces, shared understanding, persistent co-attention, representational practices, longer sequences and questioning [Investigation 17]. Within both our work and other CSCL reports, practices in mathematics education include: mathematical discourse and technical terminology; pivotal moments in problem solving and the integration of visual/graphical reasoning; numeric/symbolic expression and narrative [Investigation 12].

The idea of centering CSCL analysis on group practices emerged from study of VMT data. Publications that present that data discuss the theory, methodology and implications of the focus on group practices extensively. To ground this Investigation in that data, we point to four case studies that analyze group practices:

Study 1: A group practice of referencing

Pointing, referencing, or deixis forms a ubiquitous class of gestures essential for maintaining collaboration, including online (Stahl, 2006b). In Log 1 from Team C in the VMT SpringFest 2006, three students use a whiteboard integrated with VMT's chat tool to explore arrays of hexagons. In line 709, Jason halts discussion until he can "see" what student 137 has proposed. Qwertyuiop has drawn an array of lines to check his understanding of 137's post (Figure 1). As analyzed in (Stahl, 2013b, Sec. 8.1), this leads to work by the group to establish practices for making focal geometric figures visible to each other by coloring lines that outline or divide up the figures [Investigation 17].

line	time	student	chat post
705	19:15:08	137	So do you want to first calculate the number of triangles in a hexagonal array?
706	19:15:45	qwertyuiop	What's the shape of the array? a hexagon?
707	19:16:02	137	Ya.
708	19:16:15	qwertyuiop	ok...
709	19:16:41	Jason	wait-- can someone highlight the hexagonal array on the diagram? i don't really see what you mean...
710	19:17:30	Jason	hmm.. okay
711	19:17:43	qwertyuiop	oops
712	19:17:44	Jason	so it has at least 6 triangles?
713	19:17:58	Jason	in this, for instance
714	19:18:53	137	How do you color lines?
715	19:19:06	Jason	there's a little paintbrush icon up at the top
716	19:19:12	Jason	it's the fifth one from the right
717	19:19:20	137	Thanks.
718	19:19:21	Jason	there ya go :-)
719	19:19:48	137	Er... That hexagon.

Log 1. Excerpt from Study 1.

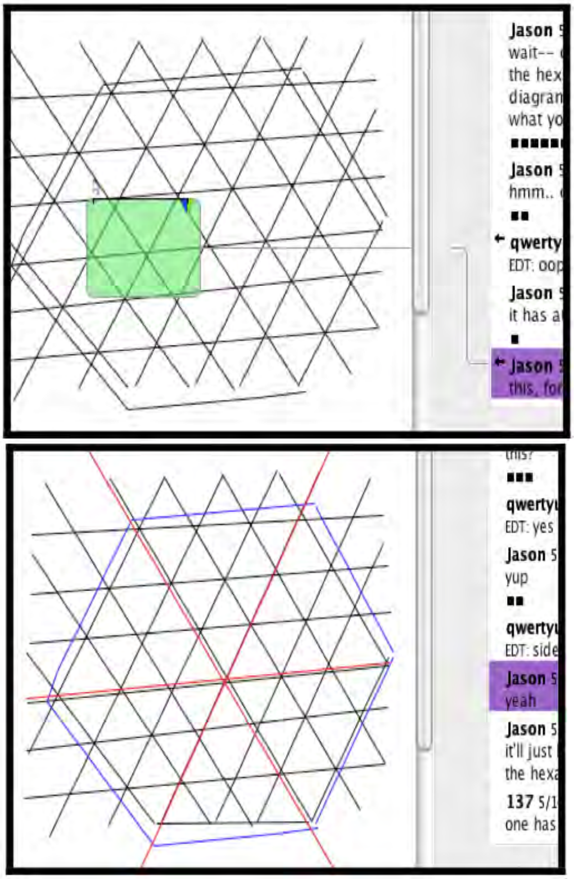

Figure 1. A large hexagon outlined with extra black lines and pointed to by a green square (left). The large hexagon divided in six sectors by red lines (right).

In the minute from his interruption of the mathematical talk at Line 709 to his resumption in Line 713, Jason demonstrates that he sees the hexagon that has been outlined by 137 in black lines (Figure 1, left), by making a new mathematical proposal and pointing from his chat posting to a small hexagon using the VMT pointing tool. Soon thereafter, the group divides the larger hexagon into six triangles using a practice involving colored lines (Figure 1, right). We also see the sharing of tool-use practices as Jason guides 137 in coloring lines in the VMT whiteboard, after which 137 colors his outline blue. Later, the group makes more complicated relationships within the array easily visible with colored lines, allowing the group to derive formulas working collaboratively step-by-step.

Study 2: Group practices over time and across individuals

In a longitudinal analysis of another VMT team—Team B in SpringFest 2006—Medina, Suthers and Vatrapu (2009) identify several group practices and show how they are enacted and repeatedly used across all four of their VMT sessions (see Figure 2).

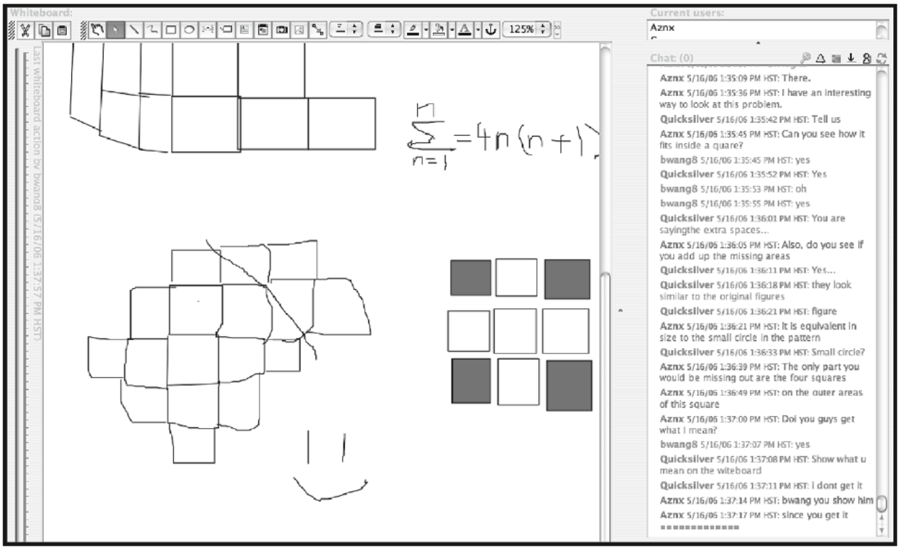

Figure 2. A growing pattern of squares forming a diamond shape, with corners filled in with colored squares to simplify calculations.

In each session, a different participant initiates interaction by first producing a whiteboard drawing that the other two subsequently orient to through chat. In their Sessions 2 and 3, the practice of *inscribe-first-solve-second* is iteratively enacted and composed with two additional practices—*modulate-perspective* and *visualize-decomposition*. In Session 2, Quicksilver's use of color and perspective emerges in the joint work in support of both representational and problem-solving practices. In Session 3, Bwang appropriates color to draw out the particular decomposition previously articulated by Aznx (Figure 2). This demonstrates both shared understanding and individual adoption of the shared group practices.

Study 3: A group practice supporting collaboration

It is particularly informative to observe novices confronting a completely new challenge. In the start of WinterFest 2013, teams of middle-school students faced VMT's multi-faceted software interface and a new form of mathematics, dynamic geometry. Here is the opening interaction of a group of three fourteen-year-old girls we call the Cereal Team (Figure 3; Log 2), analyzed in (Stahl, 2016a, Session 1).

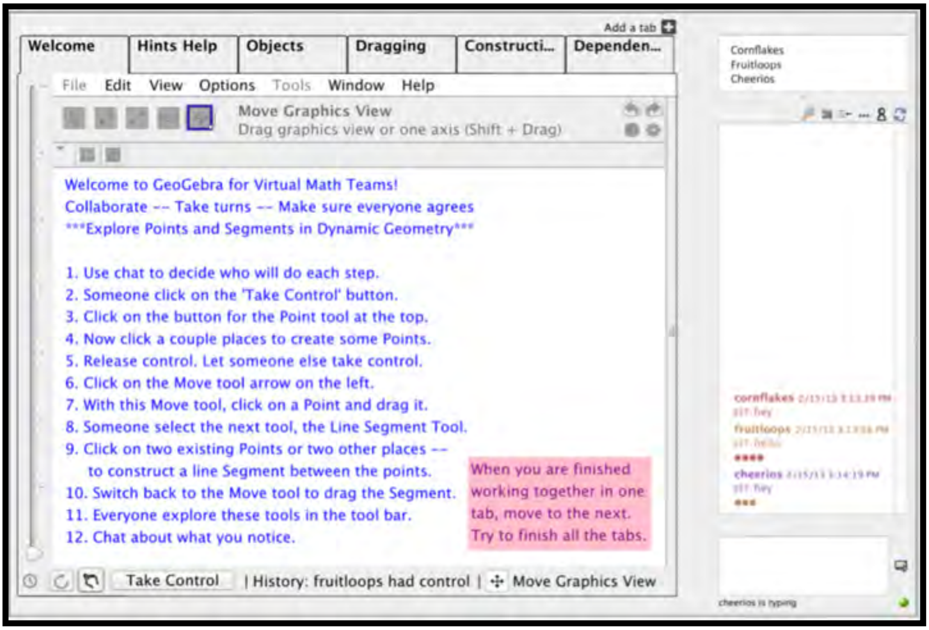

Figure 3. Students greet each other at the start of their use of VMT.

Line	**Time**	**User**	**Message**
3	13:39.4	cornflakes	hey
4	13:57.0	fruitloops	hello
6	14:19.1	cheerios	hey
7	14:45.6	cheerios	whose froot loops
8	14:53.9	cornflakes	xxxxxxxx [name *removed from log for privacy*]
9	15:10.8	cheerios	whose takimg control
10	15:20.1	cheerios	taking*
…			
21	16:18.4	cheerios	so whoses doing what
22	16:44.4	fruitloops	who wants to take control?
23	17:30.6	cheerios	xxxxxxxx do you want to [name removed for privacy]
24	17:52.2	fruitloops	no... cornflakes you take controll.....
25	18:01.7	fruitloops	who wants to do what steps?
26	18:02.9	cheerios	cornflakes take control
27	18:03.6	cornflakes	no cheerios you can
28	18:14.6	cheerios	cornflakes
29	18:25.4	fruitloops	cornflakes
30	18:33.6	cornflakes	NO
31	18:40.0	cheerios	why not
32	18:52.3	fruitloops	i just took control. lets takes turns
33	19:01.9	cheerios	alright
34	19:03.0	cornflakes	ok

Log 2. Excerpt from Study 3.

Note that the group carries over practices of greeting (lines 3, 4, 6) and correcting typos (line 10) from talking and texting to VMT. However, the group has no idea how to start computer-supported collaboration by taking control of the software and responding to the instructions. Each student strenuously resists leading the online group work. Finally, Fruitloops suggests, "Let's take turns" (Line 32). Although suggested in the instructions, this suggestion has to be stated explicitly and agreed upon by all to become an effective group practice; thereafter, each session begins by a student taking her turn, and the group work proceeds smoothly.

Study 4: A group practice of mathematical problem solving

We analyzed the Cereal Team's adoption of many group practices during their eight hour-long sessions. One of their most impressive mathematical accomplishments is analyzed in (Stahl, 2016a, Session 6). The group explores a given dynamic figure of one square inscribed in another, and then constructs its own figure with the same geometric dependencies (Figure 4).

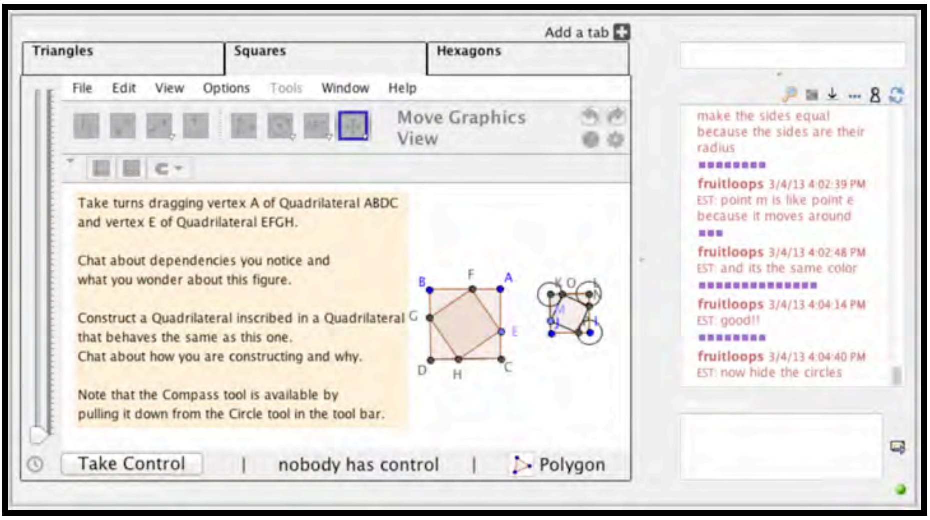

Figure 4. The team was given example square ABDC with inscribed square EFGH and the team constructs square IJKL with inscribed square MONP.

The analysis of this accomplishment and the group's discourse about it demonstrates the team's effective adoption of many mathematical, tool-usage and collaboration group practices. In particular, it makes visible how well the team members each learned the practices enacted by the group in previous sessions (Log 3, esp. Line 146).

135	39:20.3	cornflakes	olets start by cinstructing a regular square
136	39:48.0	fruitloops	i think we should make perpendicular lines somehow
137	39:58.8	cheerios	use the perpindicular line tool
138	43:21.9	fruitloops	the first line segment would be like ab
139	43:27.7	cornflakes	yes
142	51:24.7	cheerios	how do u know ji is straight
143	55:40.6	fruitloops	i dont know what to do because the points arent the same color
144	56:38.2	fruitloops	now after you make the perpendicular lines try to make the circles\
145	57:48.7	fruitloops	i think you need to know use the polygon tool and make the square
146	59:10.6	fruitloops	now we need to use the compass tool lilke we did in the triangles tab
147	59:57.5	fruitloops	because af is equal to ec and dh and bc
148	00:42.4	cheerios	i made a line segment which was if than i used the perpendicular line tool and made 2 lines on each side then used the compass tool and clicked on each point and then the center vertex was i and then made a another circle except the center vertex is j and connected all the points

Log 3. Excerpt from Study 4.

The analysis of this excerpt requires observing the shared geometric manipulations, noting the reuse of previously acquired group practices and carefully studying the text chat. The data for this is comprehensively preserved by the VMT system.

Designing for group practices

We have just summarized very briefly four case studies that were examined in considerable detail in other reports on VMT sessions. From these summaries, we can glimpse several lessons for the design of CSCL pedagogy, curriculum and technology.

Study 1 shows the importance of pointing practices (deictic reference) for establishing common ground. The VMT software provides tools for pointing from a chat posting to a region in the drawing area, for drawing lines around a region, and for coloring lines to highlight a region [Investigation 22]. The students use these to focus each other's visual attention on a referenced region. In an online environment, creating shared focus is a precondition of productive discourse. In the study's data, we can see how students discover the reference tools and how they inform other group members about them, adopting group practices of using these tools. If other groups failed to find these tools when they were needed or failed to use them appropriately, this could suggest to technology and pedagogy designers to make these tools more visible and to guide students to find and use these tools. Analysis of the group practices in this study suggests retaining the reference tools in future versions and designing more activities that explore and exploit them.

Analysis of group practices in *Study 2* contributes to the theory of CSCL, group cognition and group practice. For instance, it shows how abilities of one student become shared group practices, and how these then become abilities of the other students. Each member of the group in this study contributes a practice that may have been an individual skill or may have been brought in from the larger socio-cultural context. These become shared group practices, which then interact with other group practices, leading to innovations in collaborative mathematical cognition. Analysis focused on the creation, adoption and application of group practices can provide detailed views of computer support, collaborative knowledge building and the interplay of processes at different levels of description.

Study 3 is informative because it practically shows the creation of collaboration practices *tabula rasa*. Of course, the students are already teens with developed communication skills, but they are initially very reluctant to work together in the VMT environment (although they immediately start to explore it and work in it as individuals). The first thing that the screen of instructions (their script) says is, "Collaborate–take turns–make sure everyone agrees." Eventually the group adopts this advice and uses turn taking as a visible group practice. The students talk about whose turn it is and who will take the next turn. However, the group has to go through an adoption sequence before it can enact this group practice to overcome the team's breakdown in action. The design of the wording of the instructions resulted from the observation by the designers of previous studies, which indicated the need for group turn-taking practices. Researchers can now debate whether the instructions need further revision based on Study 3 and parallel studies with the same or re-worded instructions.

Study 4 is taken from another session by the team from Study 3, but now (five sessions later), this team of middle-school students is already achieving a geometry accomplishment that is challenging for most college-educated adults working individually. The chat excerpt reflects both geometry-construction actions and mathematical reflections by the team. An analysis of the group practices here reveals the importance of the compass tool (technology), of creating equal-length line segments (mathematics) and of explaining what one does so everyone can agree (collaboration). The group is successful because the technology, instructions and successive activities had been carefully designed to scaffold the adoption of the necessary group practices, based upon previous iterations of VMT trials.

Through analysis of the enactment of group practices while engaging in collaborative dynamic geometry, we determined that a central practice of dynamic geometry is the construction of dependencies. A *dependency* is a constraint on geometric objects that ensures invariance. For instance, in the exemplary Euclidean construction of an equilateral triangle, the sides of the triangle are constrained to be dependent on the radii of circles with equal radii, ensuring that the three sides of the triangle are of equal length to each other (Euclid's first proof). In dynamic geometry, one can drag a vertex of a triangle to make the triangle a different size or orientation; however, if the triangle has been constructed with the correct dependencies, the three sides will stay equal to each other, all getting longer or shorter together.

Geometric dependency is a very abstract notion, challenging for middle-school students to master, as can be seen in the extended analysis of the Cereal Team's group practices (Stahl, 2016). For instance, Öner (2016) [Investigation 9] specifically traces the team's struggle in their third session to move from a naïve view of geometry in terms of visual appearances to one of underlying constructed dependencies. Understanding the notion of dependencies in dynamic geometry can be operationalized in terms of identifying specific group practices of construction (which establish dependencies) and discourse (which references and reflects on the dependencies). This can then guide the researchers' analysis and design.

To learn more about effectively scaffolding group practices related to constructing and discussing dependencies, we designed activities and analyzed interaction data from trials. Our final curriculum (technology, teacher training, embedded instructions, geometry challenges, etc.) is all oriented toward fostering and supporting group practices of constructing dependencies and of discussing dependency (Stahl, 2015a). While aligned with Common Core introductory-geometry curriculum, the sequence of activities is designed to foster the successive adoption of group practices that build on each other to facilitate increasingly advanced collaboration, mathematics and argumentation. As designers, we configure activities to be used in ways we intend. However, we need to study how student teams structure their group practices in our designed environment to know how they enact our artifacts [Investigation 6]. What counts in CSCL is the actual student interaction—structured by group practices—which is always quite different from what the designers envisioned.

Just as we can see in Study 3 the team's difficulty in taking collaborative action before it has adopted the turn-taking group practice, we can repeatedly observe breakdowns in action in later sessions. Especially during periods of geometric construction, the Cereal team seems to flounder excessively. These are indications that additional group practices should be scaffolded and encouraged. For instance, there are many small tricks to doing constructions in dynamic geometry, and perhaps the curriculum should introduce some of these more explicitly for adoption as group practices. In addition, students tend to avoid discussing in chat what they are doing in the construction area. It might, for instance, be helpful to model effective geometric-construction techniques and collaborative-discussion patterns in classroom periods before small-group sessions, depending on the educational context. These are new design decisions to be made for future iterations, based on analysis of recent interaction data suggesting which possible group practices are important to support.

Analyzing group practices

Group practices are often derived from social practices (of the classroom, school mathematics, the general culture, etc.), but must be enacted or adopted and used repeatedly by the group to become effective. Groups do this in different, unpredictable ways as a result of their massively over-determined interactions. Every instance of collaborative learning is unique—it cannot be replicated or generalized. However, within a domain like collaborative online dynamic geometry, certain group practices typically recur regularly. Group practices can constitute central structural elements of group knowledge-building interactions. They structure the interaction. They also structure the domain—as practices related to dependency structure dynamic geometry. The cataloguing of group practices identified in the analysis of a corpus of interaction data from CSCL interventions can contribute to research that is directly applicable to CSCL design to support team interactions in target domains.

Traditional experimental methods aim to contribute incremental additions to a body of scientific findings. However, they are typically summative evaluations that judge the adequacy of supposedly well-defined situations, rather than formative explorations of situations under development and evolution. Summative evaluation is appropriate for studying unchanging natural phenomena. However, CSCL is a design science involving complex human interaction within social contexts in flux. We do not assume that the current design of technology, crafting of pedagogy, preparation of students, or orchestration of collaboration are finalized and perfect—ready for summative evaluation. Rather, we are interested in discovering whether we are making progress along those intermingling dimensions and how we should tweak things for our next design iteration.

In an insightful and comprehensive new review of theory and research in the domain of argumentation in education, Schwarz & Baker (2017) summarize the results of published studies on a variety of aspects of their topic. Invariably, they have to conclude that "more research on argumentation in diverse learning contexts" is needed in each aspect (p. 239). The research they are reviewing consists primarily of attempts to contribute incremental additions correlating variables and effects. What would this even mean in a field where the technology, education theory and socio-cultural context are fluid and successive studies cannot really be comparable? Furthermore, the real point in DBR research is not to evaluate the effectiveness of collaborative learning under current conditions, but to discover avenues to pursue in re-design of our tools, scripts and theories to create improved future conditions.

For a DBR science, case studies are generally more appropriate than summative evaluations (Yin, 2009). That does not mean that quantitative pre-post studies cannot be helpful in generating or checking hypotheses and suggesting phenomena to look for in detailed interaction analysis. In the VMT project, we often used quantitative and qualitative methods to pursue specific questions. However, we found that the deepest theoretical insights and the best design suggestions derived from detailed interaction analysis of interesting case studies. The examination of group practices can provide a methodological focus for such investigations in the CSCL research context.

Group practices in CSCL

The four case studies excerpted above illustrate the adoption and use of group practices for communicating (pointing), problem solving (problem decomposition), collaborating (turn taking), software usage (compass tool, perpendicular line tool) and geometric construction (of perpendiculars, squares, equal-length lines). By studying the group interactions involved in these practices, we can see in detail just what practices are needed for collaborative mathematics, how groups adopt them, and how well they are supported in our successive prototypes. This is much more useful information for CSCL theory and DBR design than just confirming that groups get a certain result more frequently under certain broad conditions.

A methodological focus on group practices can suggest the design of technologies, curriculum and pedagogy to support the adoption of key group skills. The analysis of the adoption and reuse of group practices in interaction data can pinpoint how concrete groups learn and achieve (or fail to achieve) group-cognitive accomplishments. The scaffolding of suggested group practices through the orchestration of teacher presentations before group sessions, help videos during sessions and classroom reflections after sessions can guide and enrich the collaborative-learning experience.

This new view of CSCL research suggests that CSCL should be reconceived or redefined as the design, analysis and orchestration of technology, curriculum and pedagogy to foster the adoption of productive group practices by student teams.

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11. Co-experiencing a Virtual World

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Abstract: The ability of people to understand each other and to work together face-to-face is grounded in their sharing of our meaningful natural and cultural world. CSCL groups—such as virtual math teams—have to co-construct their online, shared world with extra effort. A case study of building shared understanding online illustrates several aspects of co-experiencing a digital world. Asking each other questions is one common way of aligning perceptions. Literally looking at the same aspect of something as someone else helps us to see what each other means. The co-constructed shared world has social and temporal as well as objective dimensions. This world grounds communicative, interpersonal and task-related activities for online groups, making possible group cognition that exceeds the limits of the individual cognition of the group members.

Keywords. Questioning, bridging, seeing, world.

The Shared World of Meaning

We all find others and ourselves within one world: reality. We learn about and experience the many dimensions of this world together, as we mature as social beings. Infants learn to navigate physical nature in the arms of caregivers; toddlers acquire their mother tongue by speaking with others; adolescents are socialized into their cultures; and adults master the artifacts of the built environment designed by others. The world is rich with socially endowed meaning, and we come to perceive and experience it as immediately meaningful.

Because we share this meaningful world, we can understand each other and can work together on concerns in common. Our activities around our common objects of concern provide a shared structuring of our world in terms of implicit goals, interpersonal relations and temporal dimensions. These structural elements are reflected in our language: in references to artifacts, in social positioning and in use of tenses. All of this is understood the same by us unproblematically based on our lived experience of the shared world and communal language. Of course, there are occasional misunderstandings—particularly across community boundaries—but these are exceptions, which prove the rule of shared understanding in general.

The "problem" of establishing intersubjectivity is a pseudo-problem in most cases [Investigation 18]. Human existence is fundamentally intersubjective from the start [Investigation 15]. We understand the world as a shared world and we even understand ourselves through the eyes of others and in comparison with others (Mead, 1934/1962). Rationalist philosophy—from Descartes to cognitive science—has made this into a problem by focusing on the mind of the individual as if it were isolated from the world and from other people. That raised the pseudo-problem of epistemology: how can the (encapsulated, solipsistic) individual mind know about states of the (physical, as opposed to mental) world and about states of other minds? Rationalist philosophy (as described by Dreyfus, 1992) culminated in an information-processing view of human cognition, modeled on computer architecture: understanding is viewed as primarily consisting of a collection of mental representations (or propositions) of facts stored in a searchable memory (Newell & Simon, 1972), implemented in brain neurons.

Critiques of the rationalist approach (e.g., Dreyfus, 1992; Schön, 1983; Suchman, 1987; Winograd & Flores, 1986) have adopted a phenomenological (Heidegger, 1927/1996; Husserl, 1936/1989; Merleau-Ponty, 1945/2002), hermeneutical (Gadamer, 1960/1988), or ethnomethodological (Garfinkel, 1967) approach, in which understanding is grounded in being-in-the-world-together, in the life-world (Lebenswelt), in cultural-historical traditions and in tacit social practices. This led to post-cognitive theories, with a focus on artifacts, communities-of-practice, situated cognition, distributed cognition, group cognition, activity and mediations by actor-networks. Human cognition is now recognized to be a social product (Hegel, Marx, Vygotsky) of interaction among people, over time, within a shared world. Knowledge is no longer viewed as primarily mental representations of individuals, but includes tacit procedural knowledge (Polanyi, 1966), designed artifacts (Hutchins, 1996), representational inscriptions (Latour, 1992), small-group processes (Stahl, 2006), embodied habits (Bourdieu, 1972/1995), linguistic meanings (Foucault, 2002), activity structures (Engeström, Miettinen & Punamäki, 1999), community practices (Lave, 1991) and social institutions (Giddens, 1984). The critique of human thought as purely mental and individual is now well established for embodied reality. But what happens in virtual worlds, where the physical world no longer grounds action and reflection? That is the question for this Investigation.

Constructing a Shared Virtual World

The problem of shared understanding rises again—and this time legitimately—within the context of computer-supported collaborative learning (CSCL). That is because when students gather in a CSCL online environment, they enter a virtual world, which is distinct from (although embedded within) the world of physical co-presence. They leave the world of nature, of physical embodiment, of face-to-face perception. They enter a world that they have not all grown into together. However, this does not mean that "shared understanding" is just a matter of overlapping opinions of mental models for online groups either.

In the Virtual Math Teams (VMT) Project, we have been studying how students interact in a particular CSCL environment designed to support online discourse about mathematics. In this Investigation, we will illustrate some of our findings about how interaction in the VMT environment addresses the challenge of constructing a shared virtual world, in which small groups of students can productively engage in collaborative mathematics.

We will present a case study of Session 3 of Team C in the VMT Spring Fest 2006. Here, students aged 12-15 from different schools in the US met online for four hour-long sessions. Neither the students nor the researchers knew anything about the students other than their login user names and their behavior in the sessions. A researcher joined the students in their group sessions, but did not engage with them in the mathematics. Between sessions, the researchers posted feedback in the shared whiteboard of the environment. The VMT Project is described and discussed in (Stahl, 2009); its theoretical motivation is presented in (Stahl, 2006). The VMT environment is shown in Figure 1. The complete chat log of Session 3 of Team C is given in the Appendix to this Investigation.

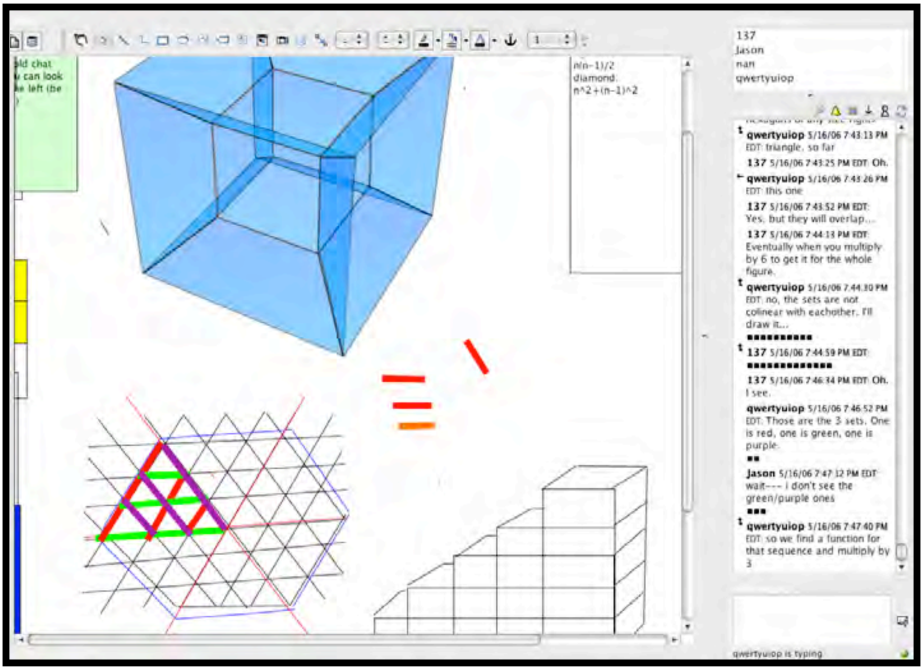

Figure 1. The VMT environment during Session 3 of Team C.

In the next four sections, we illustrate the following aspects of building shared understanding: (a) Asking each other questions is one common way of resolving or avoiding troubles of understanding and aligning perceptions. (b) Literally looking at the same aspect of something as someone else helps us to see what each other means. (c) The co-constructed shared world has social and temporal as well as objective dimensions. (d) This world grounds communicative, interpersonal and task-related activities for online groups.

Questioning to Share Understanding

We have analyzed how questions posed in the VMT environment often work to initiate interactions that resolve troubles of understanding and deepen shared understanding (Zhou, 2009; 2010; Zhou, Zemel & Stahl, 2008). This is in contrast to the rationalist assumption that questions are requests for propositional information. We will here review a number of questions from Session 3 of Group C and indicate how they lead to shared understanding. Unfortunately, due to space limitations, we will not be able to provide the full context for these questions or a detailed conversation analysis.

The question by Qwertyuiop in Log 1 (line 685) serves a coordination function, making sure that all the students have read the feedback to Session 2 before any work begins in the new Session. This is an effort, taking the form of a question, to maintain a shared experience by having everyone take this first step together.

Log 1. Question by Qwertyuiop.

Chat Index	Time of Posting	Author	Content
685	19:06:34	qwertyuiop	has everyone read the green text box?
686	19:06:44	Jason	one sec
687	19:06:45	137	Yes...
688	19:07:01	Jason	alright im done

Log 2 is part of a complicated and subtle process of co-constructing shared understanding. It is analyzed in detail in Investigation 12. The student named 137 has attempted to construct a grid of triangles in the whiteboard (similar to those in the lower left corner of Figure 1). He or she has failed (as expressed by the ironic "Great"), and has erased the attempt and solicited help by posing a question. Qwertyuiop requests clarification with another question and then proceeds to draw a grid of triangles by locating and then tweaking three series of parallel lines, following much the same procedures as 137 did. Qwertyuiop's understanding of 137's request is based not only on the "Yeah…" response to his/her "just a grid?" question, but also on the details of the sequentially unfolding visual presentation of 137's failed drawing attempt.

Log 2. Question by 137.

694	19:11:16	137	Great. Can anyone m ake a diagram of a bunch of triangles?
695	19:11:51	qwertyuiop	just a grid?
696	19:12:07	137	Yeah...
697	19:12:17	qwertyuiop	ok...

In Log 3, the moderator, Nan, asks a question to make visible in the chat what members of the group are doing. Qwertyuiop is busy constructing the requested grid in the whiteboard and the others are presumably watching that drawing activity and waiting for its conclusion. The students do not express any indication that there is a problem in their understanding of each other's activities. However, due to the nature of the virtual environment—in which the attentiveness of participants is only visible through their chat and drawing actions—Nan cannot know if everyone is engaged during this period of chat inaction. Her question and the responses to it make visible to her and to the students the fact that everyone is still engaged. The questioning may come as a minor interference in their group interaction, since Nan's questioning positions her as someone outside the group (not part of "everyone"), exerting authority by asking for an accounting, although it is intended to increase group shared understanding ("everyone know what other people are doing").

Log 3. Question by Nan.

698	19:14:09	nan	so what's up now? does everyone know what other people are doing?
699	19:14:25	137	Yes?
700	19:14:25	qwertyuiop	no-just making triangles
701	19:14:33	137	I think...
702	19:14:34	Jason	yeah
703	19:14:46	nan	good:-)
704	19:14:51	qwertyuiop	triangles are done

See What I Mean

Studies of the use of interactive whiteboards in face-to-face classrooms have shown that they can open up a "shared dynamic dialogical space" (Kershner, Mercer, Warwick & Staarman, 2010) as a focal point for collective reasoning and co-construction of knowledge. Similarly, in architectural design studios, presentation technologies mediate shared ways of seeing from different perspectives (Lymer, Ivarsson & Lindwall, 2009) in order to establish shared understanding among design students, their peers and their critics. Clearly, a physical whiteboard that people can gather around and gesture toward while discussing and interpreting visual and symbolic representations is different from a virtual shared whiteboard in an environment like VMT.

We have analyzed in some detail the intimate coordination of visual, narrative and symbolic activity involving the shared whiteboard in VMT sessions (Çakir, 2009; Çakir, Stahl & Zemel, 2010; Çakir, Zemel & Stahl, 2009) [Investigation 12]. Here, we want to bring out the importance of literally looking at some mathematical object together in order to share the visual experience and to relate to—intend or "be at"—

the object together. People often use the expression "I do not see what you mean" in the metaphorical sense of not understanding what someone else is saying. In this case study, we often encounter the expression used literally for not being able to visually perceive a graphical object, at least not being able to see it in the way that the speaker apparently sees it.

While empiricist philosophy refers to people taking in uninterpreted sense data much like arrays of computer pixels, post-cognitive philosophy emphasizes the phenomenon of "seeing as." Wittgenstein notes that one sees a wire-frame drawing of a cube not as a set of lines, but as a cube oriented either one way or another (Wittgenstein, 1953, sec. 177). For Heidegger, seeing things as already meaningful is not the result of cognitive interpretation, but the precondition of being able to explicate that meaning further in interpretation (Heidegger, 1927/1996, pp. 139f). For collaborative interpretation and mathematical deduction, it is clearly important that the participants see the visual mathematical objects as the same, in the same way. This seems to be an issue repeatedly in the online session we are analyzing as well.

In line 705 of Log 4, student 137 proposes a mathematical task for the group. This is the first time that the term "hexagonal array" is used. Coined for the first time in this posting, the term will become a mathematical object for the group as the discourse continues. However, at this point, it is problematic for both Qwertyuiop and Jason because it is new to them. In line 706, Qwertyuiop poses a question for clarification and receives an affirmative, but minimal response. Jason, unsatisfied with the response, escalates the clarification request by asking for help in seeing the diagram in the whiteboard *as* a "hexagonal array," so he can see it *as* 137 sees it. Between Jason's request in line 709 and acceptance in line 710, Qwertyuiop and 137 work together to add lines outlining a large hexagon in the triangular array. Demonstrating his ability to now see hexagons, Jason thereupon proceeds with the mathematical work, which he had halted in the beginning of line 709 in order to keep the group aligned. Jason tentatively proposes that every hexagon "has at least 6 triangles" and he makes this visible to everyone by pointing to an illustrative small hexagon from the chat posting, using the VMT graphical pointing tool.

Log 4. Proposal by 137.

705	19:15:08	137	So do you want to first calculate the number of triangles in a hexagonal array?
706	19:15:45	qwertyuiop	What's the shape of the array? a hexagon?
707	19:16:02	137	Ya.
708	19:16:15	qwertyuiop	ok...
709	19:16:41	Jason	wait-- can someone highlight the hexagonal array on the diagram? i don't really see what you mean...

710	19:17:30	Jason	hmm.. okay
711	19:17:43	qwertyuiop	oops
712	19:17:44	Jason	so it has at least 6 triangles?
713	19:17:58	Jason	in this, for instance

In Log 5, 137 asks the team to share its knowledge about how to color lines in the VMT whiteboard. Jason gives instructions for 137 to visually locate the appropriate icon in the VMT interface. Demonstrating this new knowledge, 137 changes the colors of the six lines outlining the large hexagon, from black to blue, making the outline stand out visually (see Figure 1). 137 thereby finally clarifies how to look at the array of lines *as* a large hexagon, a task that is more difficult than looking at the small hexagon that Jason pointed to. In this excerpt, the group shares their working knowledge of their virtual world (including the software functionality embedded in it), incidentally to carrying out their task-oriented discourse within that world.

Log 5. Request by 137.

714	19:18:53	137	How do you color lines?
715	19:19:06	Jason	there's a little paintbrush icon up at the top
716	19:19:12	Jason	it's the fifth one from the right
717	19:19:20	137	Thanks.
718	19:19:21	Jason	there ya go :-)
719	19:19:48	137	Er... That hexagon.

In Log 6, Jason proposes a specific mathematical task for the group to undertake, producing a formula for the number of triangles in a hexagonal array of any given side length. (As we shall see below, the group uses the term "side length" as the measure of a geometric pattern at stage n.) Qwertyuiop responds to this proposal with the suggestion to "see" the hexagon (of any size) as a configuration of six triangular areas. (To see what Qwertyuiop is suggesting, look at Figure 1; one of the six triangular areas of the large hexagonal array has its "sticks" colored with thick lines. Looking at this one triangular area, you can see in rows successively further from the center of the hexagon a sequence of 1 small triangle, then 3 small triangles, then 5 small triangles.)

Log 6. Proposal by Jason.

720	19:20:02	Jason	so... should we try to find a formula i guess
721	19:20:22	Jason	input: side length; output: # triangles
722	19:20:39	qwertyuiop	It might be easier to see it as the 6 smaller triangles.
723	19:20:48	137	Like this?

724	19:21:02	qwertyuiop	yes
725	19:21:03	Jason	yup
726	19:21:29	qwertyuiop	side length is the same...
727	19:22:06	Jason	yeah
728	19:22:13	Jason	so it'll just be x6 for # triangles in the hexagon
729	19:22:19	137	Each one has 1+3+5 triangles.

In line 723, 137 seeks confirmation that he is sharing Qwertyuiop's understanding of the suggestion. After posting, "Like this?" with a reference back to Qwertyuiop's line 722, 137 draws three red lines through the center of the large hexagon, dividing it visually into six triangular areas. Upon seeing the hexagon divided up by 137's lines, Qwertyuiop and Jason both confirm the shared understanding. Now that they are confident that they are all seeing the mathematical situation the same, namely *as* a set of six triangular sub-objects, the group can continue its mathematical work. Jason draws the consequence from Qwertyuiop's suggestion that the formula for the number of small triangles in a hexagon will simply be six times the number in one of the triangular areas of that hexagon, thereby subdividing the problem. 137 then notes that each of those triangular areas has 1+3+5 small triangles, at least for the example hexagonal array that they are looking at. The fact that the three members of the group take turns making the consecutive steps of the mathematical deduction is significant; it demonstrates that they share a common understanding of the path of deduction and are building their shared knowledge collaboratively.

The observation, "Each one has 1+3+5 triangles," is a key move in deducing the sought equation. Note that 137 did not simply say that each triangular area had nine small triangles. The posting used the symbolic visual representation, "1+3+5." This shows a pattern of the addition of consecutive odd numbers, starting with 1. This pattern is visible in the posting. It indicates that 137 is seeing the nine triangles *as* a pattern of consecutive odd numbers—and thereby suggests that the reader also see the nine triangles *as* such a pattern. This is largely a visual accomplishment of the human visual system. People automatically see collections of small numbers of objects as sets of their specific size (Lakoff & Núñez, 2000). For somewhat larger sets, young children readily learn to count the number of objects. The team has constructed a graphical representation in which all the members of the team can immediately see features of their mathematical object that are helpful to their mathematical task. The team is collaborating within a shared virtual world in which they have co-constructed visual, narrative and symbolic objects in the chat and whiteboard areas. The team has achieved this shared vision by enacting (within and for their group) practices specific to mathematics as a profession for shaping witnessed events, such as invoking related math terms and drawing each other's attention to relevant objects in the scene (Goodwin, 1994). They have learned and taught each other how to work, discuss and perceive as a group in this shared virtual world, via the adoption of group practices [Investigation 16].

Dimensions of a Virtual World

There has not been much written about the constitution of the intersubjective world as the background of shared understanding, particularly in the CSCL online context. This is largely the result of the dominance of the cognitive perspective, which is primarily concerned with mental models and representations of the world; this rationalist view reduces the shared world to possible similarities of individual mental representations. Within the VMT Project, we have analyzed the dimensions of domain content, social interaction and temporal sequencing in the co-construction of a virtual math team's world or joint problem space (Sarmiento & Stahl, 2008; Sarmiento-Klapper, 2009a; Sarmiento-Klapper, 2009b). In this work, we have found the following conceptualizations to be suggestive and helpful: the "joint problem space" (Teasley & Roschelle, 1993) and the "indexical ground of reference" of domain content (Hanks, 1992); the social "positioning" of team members in discourse (Harré & Gillet, 1999) and their self-coordination (Barron, 2000); and the temporal sequentiality of discourse (Schegloff, 1977) and the bridging of temporal discontinuities.

In its previous sessions, Team C had tried to derive formulae for the number of two-dimensional objects (small squares or small triangles) in a growing pattern of these objects, as well as the number of one-dimensional sides, edges or "sticks" needed to construct these objects. A major concern in counting the number of sides is the issue of "overlap." In a stair-step two-dimensional pattern (like the 2-D version of the stair-step pyramid in the lower right section of Figure 1), one cannot simply multiply the number of squares by 4 to get the number of sides because many of the sides are common to two squares. In Session 1, Team C had seen that in moving from one stage to the next stage of the stair-step pattern most new squares only required two new sides.

In Log 7, Qwertyuiop moves on from the derivation of the number of triangles to that of the number of sides. He "bridges" back to the group's earlier insight that the addition of "each polygon corresponds to [an additional] 2 sides." In bridging to past sessions, we found, it is necessary for a group to re-situate a previous idea in the current context. In line 731, Qwertyuiop is reporting that for their hexagon formula, such situating does not work—i.e., that the current problem cannot be solved with the same method as the previous problems. The team then returns to the formula for the number of triangles and efficiently solves it by summing the sequence of consecutive odd numbers using Gauss' technique—the sum of n consecutive odd integers is n(2n/2)—which they had used in previous sessions.

Log 7. Bridging by Qwertyuiop.

731	19:22:29	qwertyuiop	the "each polygon corrisponds to 2 sides" thing we did last time doesn't work for triangles
732	19:23:17	137	It equals 1+3+...+(n+n-1) because of the "rows"?
733	19:24:00	qwertyuiop	yes- 1st row is 1, 2nd row is 3...
734	19:24:49	137	And there are n terms so... n(2n/2)
735	19:25:07	137	or n^2
736	19:25:17	Jason	yeah
737	19:25:21	Jason	then multiply by 6
738	19:25:31	137	To get 6n^2

In Log 8, Qwertyuiop makes a particularly complicated proposal, based on a way of viewing the sides in the large hexagon drawing. He tries to describe his view in chat, talking about sets of collinear sides. Jason does not respond to this proposal and 137 draws some lines to see if he is visualizing what Qwertyuiop has proposed, but he has not. Qwertyuiop has to spend a lot of time drawing a color-coded analysis of the sides as he sees them.

Log 8. Proposal by Qwertyuiop.

742	19:25:48	qwertyuiop	an idea: Find the number of a certain set of colinear sides (there are 3 sets) and multiply the result by 3
746	19:26:36	137	As in those?
747	19:27:05	qwertyuiop	no-in one triangle. I'll draw it...
748	19:28:10	qwertyuiop	those
749	19:28:28	qwertyuiop	find those, and then multiply by 3
750	19:28:50	137	The rows?
751	19:30:01	qwertyuiop	The green lines are all colinear. There are 3 identical sets of colinear lines in that triangle. Find the number of sides in one set, then multiply by 3 for all the other sets.
752	19:30:23	137	Ah. I see.

He has decomposed the set of sides of one triangular area into three subsets, going in the three directions of the array's original parallel lines. He can then see that each of these subsets consists of 1+2+3 sides. There are 3 subsets in each of the 6 triangular areas. Based on this and generalizing to a growing hexagonal array, which will have sums of consecutive integers in each subset, the team can derive a formula using past techniques.

At some point, they will have to subtract a small number of sides that overlap between adjacent triangular areas. Qwertyuiop has proposed a decomposition of the hexagonal array into symmetric sets, whose constituent parts are easily visible. Thus, his approach bridges back to previous group practices, which are part of the shared world of the group—see the analysis of a similar accomplishment by Group B in (Medina, Suthers & Vatrapu, 2009). The hexagonal pattern, which Team C came up with on its own, turns out to be considerably more difficult to decompose into simple patterns that the original problem given in Session 1. It strained the shared understanding of the group, requiring the use of all the major analytic tools they had co-constructed (decomposing, color-coding, visually identifying sub-patterns, summing series, eliminating overlaps, etc.).

In Log 9, the group work is interrupted by an interesting case of bridging across teams. At the end of each session, the teams had posted their findings to a wiki shared by all the participants in the VMT Spring Fest 2006. During their Session 3, Team B had looked at Team C's work on a pattern they had invented: a diamond variation on the stair-step pattern. In their wiki posting, Team C had used their term, "side length." Because members of Team B did not share Teams C's understanding of this term, they were confused by the equation and discussion that Team C posted to the wiki. Team B's question sought to establish shared understanding across the teams, to build a community-wide shared world. As it turned out, Team C had never completed work on the formula for the number of sides in a diamond pattern and Team B eventually discovered and reported the error in Team C's wiki posting, demonstrating the importance of community-wide shared understanding.

Log 9. Bridging by Nan.

804	19:48:49	nan	(we got a question for you from another team, which was posted in the lobby:
805	19:48:53	nan	Quicksilver 7:44:50 PM EDT: Hey anyone from team c, our team needs to know what n was in your equations last week
806	19:49:04	Jason	oh
807	19:49:15	137	The length of a side.
808	19:49:16	qwertyuiop	was n side length?
809	19:49:33	Jason	are you talking about the original problem with the squares
810	19:49:48	137	I think nan is.

811	19:49:58	qwertyuiop	i think it's squares and diamonds
812	19:49:58	Jason	oh
813	19:50:12	Jason	then if you look in the topic description, theres a column for N;
814	19:50:14	Jason	thats what it is
815	19:50:17	nan	ok, quicksilver said they got it
816	19:50:25	Jason	so yes it is # sides
817	19:50:26	nan	thanks guys

Grounding Group Cognition

CSCL is about meaning making by groups (Stahl, Koschmann & Suthers, 2006). At its theoretical core are questions about how groups of students collaborating online co-construct and understand meaning. In this essay, we conceptualize this issue in terms of online groups, such as virtual math teams, building a shared meaningful world in which to view and work on mathematical objects.

Log 10 illustrates a limit of shared understanding, closely related to the notion of a "zone of proximal development" (Vygotsky, 1930/1978, pp. 84-91). The original stair-step pattern consisted of one-dimensional sides and two-dimensional squares. In their Session 2, Team C had generalized this pattern into a three-dimensional pyramid consisting of cubes. Now Qwertyuiop proposes to further generalize into a mathematical fourth dimension and derive formulae for patterns of one, two, three and four-dimensional objects. He had previously imported a representation of a four-dimensional hyper-cube (see the upper area of Figure 1) into the whiteboard for everyone to see.

Log 10. Generalization by Qwertyuiop.

20:12:22	qwertyuiop	what about the hypercube?
20:12:33	137	Er...
20:12:39	137	That thing confuses me.
20:13:00	137	The blue diagram, right?
20:13:13	qwertyuiop	can you imagine extending it it 4 dimensions, and a square extends into a grid?
20:13:17	qwertyuiop	yes
20:13:30	137	I didn't get that?
20:13:32	qwertyuiop	I'm having trouble doing that.
20:13:45	qwertyuiop	didn't get this?
20:13:50	137	Ya.

20:15:02	qwertyuiop	If you have a square, it extends to make a grid that fills a plane. A cube fills a space. A simaller pattern of hypercubes fills a "hyperspace".
20:15:19	137	The heck?
20:15:29	137	That's kinda confusing.
20:15:43	qwertyuiop	So, how many planes in a hyper cube latice of space n?
20:16:05	137	Er...
20:16:07	qwertyuiop	instead of "how many lines in a grid of length n"
20:16:17	qwertyuiop	does that make any sense?
20:16:30	137	No. No offense, of course.

At this point late in Session 3, Jason had left the VMT environment. Qwertyuiop was unable to guide 137 to see the drawing in the whiteboard as a four-dimensional object. Apparently, Qwertyuiop had been exposed to the mathematical idea of a fourth dimension and was eager to explore it. However, 137 had not been so exposed. They did not share the necessary background for working on Qwertyuiop's proposal. The only resource available for scaffolding joint meaning making on this topic was the graphic that Qwertyuiop imported—and that was apparently not enough by itself.

This shows that tasks for student groups, even tasks they set for themselves, need to be within a shared group zone of proximal development or be adequately supported by the collaboration environment. The stair-step problem was in their zone—whether or not they could solve it themselves individually, they were able to solve it collectively, with enough shared understanding and background knowledge that they could successfully work together. Their three-dimensional pyramid turned out to be quite difficult for them to visualize in a shared way. Their diamond pattern seemed to be easy for them, although they forgot to work on some of it and posted an erroneous formula. The hexagonal array required them to develop their skills in a number of areas, but they eventually solved it nicely. However, the hyper-cube exceeded at least 137's ability (or desire) to participate in investigating it.

Rationalist philosophy reduces the complexity of social human existence to a logical, immaterial mind that thinks about things by representing them internally. It confuses the mind with the brain and conflates the two. It assumes that someone thinking about a hexagon or working on a math problem involving a hexagon must primarily be representing the hexagon in some kind of mental model. But one of the major discoveries of phenomenology (Husserl, 1936/1989) was that (mental) intentionality is always the intentionality of some (non-mental) object and that cognition takes place as a "being-with" that object, not as a mental act of some transcendental ego [see Investigation 18].

As an example, we have seen that the members of Team C are focused on the graphical image of the hexagon in their virtual world on their computer screens. They reference this image and transform it with additional lines, colors and pointers. They chat about this image, not about some personal mental representations. They work to get each other to see that image in the same way that they see it. This "seeing" is to be taken quite literally. Their eyes directly perceive the image. They perceive the image in a particular way (which may change and which they may have to learn to see).

"Seeing" is not a metaphor to describe some kind of subjective mental process that is inaccessible to others, but a form of contact with the object in the world. Accordingly, we may say that shared understanding is a matter of the group members being-there-together at the graphical image in the whiteboard.

Being-there-together is a possible mode of existence of the online group. The "there" where they are is a multi-dimensional virtual world. This world was partially already there when they first logged in. It included the computer hardware and software. It included the VMT Spring Fest as an organized social institution. As they started to interact, the students fleshed out the world, building social relationships, enacting the available technology, interpreting the task instructions and proposing steps to take together. Over time, they constructed a rich world, furnished with mathematical objects largely of their own making and supporting group practices that they had introduced individually but which they had experienced and adopted as a group [Investigation 16].

Being-there-together in their virtual world with their shared understanding of many of this world's features, the group was able to accomplish mathematical feats that none of them could have done alone. Each individual in the group shared an understanding of their group work at least enough to make productive contributions that reflected a grasp of what the group was doing. Their group accomplishments were achieved through group processes of visualization, discourse and deduction. They were accomplishments of group cognition, which does not refer to anything mystical, but to the achievements of group interaction. The group cognition was possible because of, and only based upon, the shared understanding of the common virtual world. Shared understanding is not a matter of similar mental models, but of experiencing a shared world.

Of course, there are limits to group cognition, just as there are limits to individual cognition. We saw that Team C could not understand Qwertyuiop's ideas about the fourth dimension. Without shared understanding about this, the group could not engage in discourse on that topic. Group cognition can exceed the limits of the individual cognition of the group members, but only by a certain amount. The individuals must be able to stretch their own existing understanding under the guidance of their peers, with the aid of physical representations, tools, concepts, scaffolds and similar artifacts, whose use is within their grasp—within their zone of proximal development (Vygotsky, 1930/1978). We have seen that Team C was able to solve a complex mathematical problem that they set for themselves involving a hexagonal array by building up gradually, systematically and in close coordination a meaningful virtual world.

An analysis of the log of the interaction in our case study has demonstrated much about the team's group cognition. Their group work proceeded by contributions from different individuals, with everyone contributing in important ways. Their questions showed that their individual cognition was initially inadequate to many steps in the work; but their questions also served to expand the shared understanding and to ensure that each member shared an understanding of each step. Because the students demonstrated an understanding of the group work through their successive contributions, we can see not only that individual learning took place, but we can analyze the interactional processes of group learning or group cognition through which it took place by detailed analysis of the chat and drawing actions.

As Vygotsky argued, not only does group cognition lead individual cognition by several years, but individual cognition itself develops originally as a spin-off of group cognition. Individuals can learn on their own, but the cognitive and practical skills that they use to do so are generally learned through interaction with others and in small groups.

This is a powerful argument for the use of CSCL in education. It is incumbent upon CSCL research to further analyze the processes by which this takes place in the co-construction of shared understanding within co-experienced virtual worlds. As we have seen, participants in CSCL virtual environments co-construct worlds to ground their interactions. These virtual worlds exploit intersubjective meaning-making, perceptual joint attention and referential practices learned in the physical social world and adapted to the co-experienced online world.

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12. From Intersubjectivity to Group Cognition

Abstract. The term "intersubjectivity" is ambiguous. It can refer to the problem of how two or more minds can inter-relate: understand each other and work together from their individual cognitive positions. It can also refer to a form of joint cognition that is shared by a group and transcends, unifies or even founds the cognition of the participating individuals. This Investigation traces an historical evolution in philosophy from the former view to the later, considering in turn Plato, Descartes, Kant, Husserl, Schutz, Heidegger, Merleau-Ponty, Tomasello and Vygotsky. It proposes a view of intersubjectivity as group cognition, appropriate to CSCW and CSCL, illustrated with a CSCW example of paired programming and a CSCL example from online collaborative geometry.

Keywords. Intersubjectivity, shared understanding, joint intentionality, we-awareness, group cognition, group agency, joint participation, perspectival individuality, joint attention, shared meaning making, being-there-with-others, shared world.

The Issue of Intersubjectivity

The question of how it is possible for people to understand each other has been a controversial theme throughout the history of philosophy. It is a foundational issue for the social sciences, in which researchers try to understand the behaviors and statements of other people. It is of particular relevance to Computer-Supported Cooperative Work (CSCW) and Computer-Supported Collaborative Learning (CSCL), where participants have to understand, work with and learn with each other. Philosophers have posed the issue of how an individual can understand another and how a small group or community can have a joint understanding, shared intentionality or we-awareness. Studies of CSCW not only adopt insights from the philosophy of intersubjectivity to ground their methodology, but they also contribute to the analysis of how intersubjectivity is established in concrete settings, including in virtual environments. Similarly, CSCL research can investigate how groups of people learn to construct intersubjective understandings in both traditional and technologically enhanced interactions. While classical phenomenology of intersubjectivity started from the cognitions of a solitary mind, the notion of intersubjectivity has subsequently shifted to a more social view. Recent studies of intersubjectivity suggest a structure of group cognition, which can provide a foundation for collaboration in work and learning that incorporates but transcends individual cognition.

While "intersubjectivity" is a modern term, it points to an issue that is both as old as philosophy and as current as the lead article in a CSCW journal special issue on the topic (Tenenberg, Roth & Socha, 2015). Intersubjectivity is what makes we-awareness possible. By referencing a realm between or encompassing multiple people, intersubjectivity raises the question of whether knowing, thinking or being aware are at base matters of individual consciousnesses or of collectivities. The following historical review of the philosophy of intersubjectivity will trace a shift from a foundation in solitary minds to one in human groups or communities. It will consider the central statements concerning intersubjectivity from: Husserl, Schutz, Heidegger, Merleau-Ponty, Hegel, Marx, Vygotsky and Tomasello. Implications of the philosophic conception of intersubjectivity for CSCW and CSCL methodology—in which the analytic foundation in individual or group cognition is currently highly contentious—will then be suggested and be related to research in these fields.

The issue of intersubjectivity is paramount to our times. The major geo-political issues of the day concern how people around the shrinking globe can understand each other and relate in unity to their shared world. How can the rich and the poor see eye to eye on global ecology; how can former colonial powers and former colonies work together for peace and mutual benefit; how can populations with incompatible politics, ideology, religion and economic interests co-exist? We do not adequately grasp how people understand each other even in dyads, let alone in international communities. Researchers in CSCW and CSCL could contribute to such a comprehension, but they tend to get distracted with methodological concerns based on outmoded philosophies and approaches misappropriated from the natural sciences.

The problematic of intersubjectivity emerged in response to the growth of the social sciences a century ago. The first explicit systematic discussion was in the phenomenology of Husserl, grappling with issues in traditional philosophy. Although the historical movement from intersubjectivity to group cognition followed multiple intertwined paths, this Investigation will present a single conceptual thread. It will review the core discussions of intersubjectivity in the primary philosophic texts that defined the concept. As we will see, the term "intersubjectivity" is ambiguous. It can refer to the problem of how two or more minds can inter-relate: understand each other and work together from their individual cognitive positions. It can also refer to a form of joint cognition that is shared by a group and transcends, unifies or even founds the cognition of the participating individuals. This Investigation will trace an evolution in philosophy from the former view to the later, and will propose a view of intersubjectivity as group cognition, appropriate to CSCW and CSCL.

The Philosophy of Subjectivity: Plato, Descartes, Kant

Socrates was the poster child for the self-reflective individual, who radically examined his own life and thought. However, in the end he submitted to Athenian society as the collectivity to which he fundamentally belonged. Perhaps horrified by the consequence of Socrates' refusal to break with his corrupt, irrational and unheeding community, Plato (340 BCE) metaphorically left his fellow citizens behind in the dark cave of their traditions and illusions to emerge into true knowledge as an isolated individual. Thenceforth, truth, knowledge and learning were no longer matters founded in traditional society, but concerned eternal ideas discoverable through individual critical reflection.

The focus on individual thought found its ultimate formulation in Descartes (1633). In his argument—popularly formulated as "I think, therefore I am"—Descartes claimed that as much as he tried to doubt the reality of everything, he could not doubt that he was thinking, because his doubt was itself an instance of him thinking. If he was thinking, then there must be a subject (namely him) who was doing the thinking. Descartes thereby established as a foundation for philosophy and all knowing that an individual thinking subject existed. This raised subsequent problems, which were much harder for Descartes and his successors to address: how can this radically doubting individual subject be certain about knowledge of any object in the physical world (the problem of epistemology) and how can this isolated individual subject be certain about knowledge of other people's minds (the problem of intersubjectivity). How can one even know that a world or that other people exist external to the individual thinking subject (the problem of solipsism)?

There were many attempts to address the problems left in Descartes' wake. These produced philosophies of empiricism, rationalism, materialism, idealism, etc. Some principles from these classical philosophies were adopted as foundations of scientific method and are still assumed in many contemporary research methodologies. Kant (1787) came up with a synthesis of the major philosophic approaches of his time, still focusing on the individual human mind as the seat of pure reason. He argued that the only access we have to the world is to versions of objects that we have constructed ourselves from our sense perceptions. We structure what we sense from the world that is external to our individual minds. We do so in terms of categories of time, space and causality, which we impose in constructing the world as meaningful and knowable. That provides us with a view of the world that makes sense to us, with persistent, meaningful objects. Kant's solution to the problem of epistemology provides a form of constructivism that makes impossible "objective" knowledge (other than logical deductions) in a naïve sense. Kant demonstrated that there are many questions that are meaningless to pose—often because they presume to peek behind the constructions that our understanding of the world unavoidably erects.

The Phenomenology of Intersubjectivity: Husserl

While philosophy has always been concerned with the nature of subjectivity, the first major discussion of inter-subjectivity was by Husserl. He devoted his popular introduction to phenomenology to the problem of intersubjectivity. His *Cartesian Meditations* (Husserl, 1929) was presented at the Sorbonne in 1929. (Merleau-Ponty was in the audience as a student.) This was a couple years after Husserl's student and assistant, Heidegger, had published *Being and Time*, but Husserl's presentation was as yet unaffected by that. Husserl was concerned with the crisis of the philosophical foundations of the sciences. Dilthey and others had differentiated the human sciences from the natural sciences. Einstein and quantum theory were shaking the physical sciences with the idea that observation was relative to the observer. The foundations of logic and mathematics were in dispute. Weber and others were formulating social sciences (linguistics, anthropology, as well as sociology) in terms of meaning and interpretation, hard to objectify.

Husserl began from Descartes' argument. It starts with the solitary subject ("I") doubting everything except its own existence. In five chapters or "meditations," Husserl builds toward the central problem, intersubjectivity: How can I know another person—that he[4] exists or what he means when he speaks? For a social science today, such as CSCW or CSCL, this asks: How does one person relate to co-workers or fellow students as equally human, how does one understand the meaningful actions and statements of others? Also: How does a researcher analyze the meaning created in the discourse and in the work products of cooperating workers or collaborating students?

After introducing Descartes' position in his first meditation, Husserl shows how minds construct meaningful objects. At first, cognition is intentional, that is, directed toward some phenomenon.[5] For instance, if my consciousness is directed toward a six-sided die, I perceive at any instant only evidence of certain sides. However, over time my consciousness can synthesize the die as having six sides, perceptible from different perspectives. Then the die is intended by my consciousness as "given" with more than the immediate evidence. The meaningful die is temporally constituted by a series of perceptions and synthesizing acts in my stream of consciousness. I understand the perceived view of the die as having a horizon of possibilities, anticipations or potential remembrances that is given with the immediate perception

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[4] The masculine pronoun is used here to refer to people of all genders, in keeping with traditional English grammar and philosophic usage.

[5] The notion of intentionality was first developed by Husserl's teacher, Brentano (1874). Intentionality means that consciousness is always consciousness *of* something, always directed at something. Consciousness is not a purely mental phenomenon but extends into the "external" world.

as belonging to the meaning of the phenomenon of the observed view of the die. Husserl's third and fourth meditations outline his extensive phenomenological analyses of how the solitary subject constitutes his world and his lived temporality, starting from elementary cognitive experiences.

For Husserl, we construct or constitute our experiences of things, including other people, through sequences of cognitive acts, which are generally not conscious, but pre-reflective. Our knowledge of another person is constituted through our own processes of constructing our experience of them. We can, for instance, construct an understanding of someone else's behavior as the behavior of a person who is human like us, has a stream of consciousness like ours and has understandings like ours. We can assemble evidence for our understanding of the other person from experiences we have had—both our experiences of the other person and our own experiences that are similar or relevant. For instance, we observe our own bodies and those of others—and we see that the other is like us.

In his concluding fifth meditation, Husserl reaches the goal of his presentation and gives us a summary of the first major extended analysis of intersubjectivity. He departs from Descartes and argues that we can experience other people as also sentient beings who experience the world as we do. In fact, this makes the world a shared, intersubjective one. We experience the socially shared world from our own perspective, and we see other people as also experiencing this same world from their positions:

> I experience others in shifting experiential manifolds. On the one hand, as objects in the world. Not just as mere natural things, but also experienced as psychically active in the natural bodies to which they each belong. On the other hand, I experience them simultaneously as subjects of this world, as experiencing this world—this same world that I experience myself. They are experiencing it with me, as I experience it and as within it, I experience them.
>
> Even within my purely cognitive life, I experience the world including other people and the associated meaning not as a so-to-say private construction of synthesis, but as other than mine, as *intersubjective*, as existing for everyone, as having its objects accessible to everyone….
>
> To the character of the world and particularly of nature as objective, there belongs its being there for everyone, as constituted by us whenever we speak of objective reality. To this belongs the objects of the experienced world having mental characteristics, which refer to human subjects by their origins and meaning—and in general refer to other subjects and their actively constituting intentionality. This includes all cultural objects (books, tools and all kinds of works, etc.), which also carry with them the experiential meaning of being there for everyone. That is, for everyone of

> the corresponding cultural community, such as the European or more specifically the French. (Husserl, 1929, §43, my translation)

Husserl overcomes the solipsism of Descartes by showing that I experience others as fellow subjects in a shared world. However, this all takes place in my own consciousness and experiences. So, it is not meaningful to ask if my understanding of the other person's behavior is identical to the other person's understanding of their own behavior. The gulf of intersubjectivity is spanned by Husserl in that we can construct an understanding of the other person as a person, having their own understandings. Nevertheless, we cannot erase the gulf and obtain direct knowledge of their understanding. Any two people construct their own understanding of the shared world (including themselves and each other) from the perspective of their own subjectivity (stream of consciousness, personality, personal history, body position, etc.).

The Social Science of Intersubjectivity: Schutz

Schutz explicitly applied Husserl's approach to the social sciences, specifically to Weber's sociology. In 1932, he published a detailed and relatively clear book on the meaning-full construction of the social world (Schutz, 1932), centered around a chapter on "Foundations of a theory of intersubjective understanding." While occasionally referencing Heidegger, Schutz remained true to Husserl's phenomenology, starting from the cognitions of an individual consciousness and constructing the intersubjective world upon that basis. This was also consistent with the methodological individualism of Simmel and Weber, which held that "all concrete social phenomena should be traced back to the modes of individual behavior" (Schutz, 1932/1967, p. 4).

Schutz starts from Husserl's conclusion of the intersubjectivity of the world, namely that people take for granted the existence of other people as having the same kinds of temporal streams of consciousness and as sharing the same social world. However, since people constitute the world from their own perspective (in terms of their own bodily location, personal history, ingrained habits, action goals and subjective experiences), "the concept of the other person's intended meaning remains at best a limiting concept" (p. 98). We can only approach an understanding of another's cognition to a degree and without certainty.

To understand another person takes a reflective act. The other person typically does not understand his own action in this way: he is simply acting, not reflecting on his action. Thus, it does not even make sense to ask if a researcher's understanding of a subject's action corresponds to the subject's own understanding, since the subject probably does not have that kind of reflective understanding. If a researcher tries to triangulate his interpretation by asking a subject questions (in a test, a questionnaire, an interview, a focus group), then the subject may start to reflect on the relevant prior actions, but his newly constructed understanding or response was not something present at the time of the action, let alone motivating it in advance or causing it. Nor is the subject's retroactive self-understanding qualitatively superior to an observer's understanding of the subject, except that the subject may have access to a richer array of information about himself and his past. Like the researcher's analysis, the subject's self-understanding is also a speculative reconstruction from a series of perceived experiences.

Schutz provides analyses of meaning making, sign systems and artifacts, as they enter into our understanding of other people and of their communications, actions and interactions. He also describes concepts of "in-order-to motives" and "because motives," which can be used for understanding statements and actions, without attributing explicit knowledge to the actor. These feed into Schutz' interesting discussions of (a) the thou-orientation, (b) the we-relationship, (c) face-to-face situations and (d) direct social observation.

(a) The *thou-orientation* is a pre-reflective awareness of another person as a fellow human, who has consciousness and experiences similar in kind to my own. It thus embodies the intersubjectivity in which others are recognized as indubitable, aware, thoughtful and human. To understand another in this way is to attribute meanings, desires and plans to him. It is the first stage of intersubjectivity as a relationship between two individual subjects.

(b) When the thou-orientation becomes reciprocal, it forms a *we-relationship*, in which another and I experience the world together as a shared world. Schutz provides this example: "Perhaps while I was following the bird's flight, I noticed out of the corner of my eye that your head was moving in the same direction as mine. I could then say that the two of us, that *we*, had watched the bird's flight" (p. 165). Although we have experienced something together, that does not mean that we had the same subjective experience. For me to think about your experience, I have to step back from our we-relationship and reflect on evidence about your experience that are available to me. This is a second stage of intersubjectivity including reciprocity: I am aware that you are experiencing the same world as I am, and we are doing it together.

(c) When two people are engaged *face-to-face*, they participate together in an ongoing series of acts of meaning-establishment and meaning-interpretation (such as elicitation/response pairs of discourse utterances, in which I say something and you respond, thereby establishing the meaning of my utterance through its implicit interpretation by your response). In orienting to objects of joint attention, the participants experience the objects as common to both their experiences. They are simultaneously aware of what each other experiences as being experienced together. The shared intersubjective world is constituted by this experience in the face-to-face situation. Over time, I understand my partner in terms of his motives (personality, habits). Furthermore, I can check my understanding of the other by asking him questions (e.g., to jointly create meaning and to avoid or repair potential misunderstandings). This all takes place within the merged experiential streams of the face-to-face situation. Although Schutz does not discuss the face-to-face mode of intersubjectivity in any detail, he hints here at an intersubjectivity that is more than the sum of its parts, the two individual subjectivities. Meanings are created through the interaction between the participants; there are group processes like repair of understandings; and the experience of the world is partially shared, not completely subjective. Schutz' face-to-face intersubjectivity provides a brief foretaste of group cognition.

(d) Schutz then contrasts the face-to-face situation (e.g., of participants collaborating) with *direct social observation* (e.g., by a social-science researcher). Direct social observation is very different from the face-to-face situation. The observer is not engaged in the same undertaking as his subject, nor is he engaged with the subject in a shared context of action. Furthermore, the observer does not have the same kinds of access through interaction to check on and repair his understandings of the subject's subjective experiences, motivations or attempts. The close mutuality and reciprocal mirroring of the face-to-face situation is missing in a context of objective observation. Schutz specifies three possible indirect approaches for scientific observation of a subject's motives: An observer can interpret the subject's behavior in terms of what he imagines he himself might have done under the circumstances. Alternatively, he can take into account the customary behavior of that kind of person (e.g., applying Weber's ideal types). Finally, he can interpret the observed behavior "in terms of the effect which it actually has and assume that the effect is what was intended" (p. 175). These modes of understanding other people and of intersubjectivity appear in various methodologies of CSCW and CSCL research.

The Being of Intersubjectivity: Heidegger

By the time Husserl's and Schutz' analyses of intersubjectivity were published, Heidegger's implicit repudiation of these theories was already widely read. Although Heidegger emerged from the Husserlian school of phenomenology and was deeply steeped in traditional philosophy, his *Being and Time* presented a radical rejection of the starting point of individual consciousness. In this sense, he left behind not only the constructivism of Kantian pure reason, but also the cognitivism of any methodological individualism. Heidegger's analysis of human existence began with the unity of being-in-the-world, where people exist through their essential involvement in the world. This involvement includes being-there-together in the shared world with other people.

Heidegger's analysis of being-there-with-others (Heidegger, 1927, §§25-27) is laced with barbs against the positions of Husserl and Schutz. Heidegger refers to the enterprise of seeking a transition from the isolated individual to the other as a "misunderstanding" and explicitly rejects the conception of the unity of the self "as the identity of the I maintaining itself in the multiplicity of its 'experiences'" (p. 122).

Human being—as our openness to the world—is defined according to Heidegger, first and foremost, by the collectivity of other people, with whom we are concerned and with whom we share a joint world, filled with meaningful artifacts and natural objects that we deal with together. However, this collectivity is described abstractly by Heidegger—not in terms of our family, friends, colleagues, neighbors, community or society. In fact, it is portrayed in rather dark tones, as an oppressive or at least obscuring view of the world through the outlook of an unenlightened mass culture.

Heidegger argues that because we are caught up in this distracting and obscuring culture and are constantly busily distracted by other people, with the objects in the world of our concern and in our projects involving them, we cannot see our own true nature as being-there-with-others. Rather, we see things—including other people and even ourselves—in terms of an ontology of physical objects and mental ideas (*à la* Plato, Descartes and the common sense of the collective). Unfortunately, after his brief but central and pivotal analysis of being-there-with-others, Heidegger shifts from the social basis of human existence, which he had finally uncovered, to a focus on the individual self as a secondary ontological mode, which supposedly provides greater understanding of human being than the collective view. He values this derived mode as more "authentic," although ironically it is close to the individualistic reflective mode of Husserl. Heidegger, thus, retreats from the social foundation he briefly established. By not elaborating this more concretely through contact with the other mainstream of German philosophy developed by Hegel and Marx, Heidegger remains at the level of politically conservative cultural criticism (Adorno, 1964/1973) and heads toward his fateful political error (Stahl, 1975).

The Corporeality of Intersubjectivity: Merleau-Ponty

Merleau-Ponty studied both Husserl and Heidegger carefully, including especially their responses to Descartes' problem of intersubjectivity [6]. Merleau-Ponty (1945/2002) fleshed out their analyses with an in-depth analysis of the role of the body and of embodied perception in human being and thinking. His chapter on other

[6] When Merleau-Ponty died, he was found with his head literally in a book by Descartes, perhaps struggling to the end with the question of intersubjectivity.

people and the human world comes as the culmination of his phenomenological description of human existence. He argues that the experience of another person—such as my sense of the other's grief or anger—is given immediately in my perception of his bodily contact and expression, not mediated through some form of my reflection on what his inner experiences must be like based on remembrances of similar experiences of my own (p. 356). We thus strive to project a shared world, in which we can communicate, for instance about our grief or anger. We each do so from our own bodies, as corporeal actors.

Intersubjectivity is given with our being embodied in a shared world and forms a basis for our subjectivity. Intersubjectivity could not be "constituted" subsequently by isolated individual consciousnesses. As Merleau-Ponty says, "My greatest attempt at impartiality would never enable me to prevail over my subjectivity (as Descartes so well expresses it by the hypothesis of the malignant demon), if I had not, underlying my judgments, the primordial certainty of being in contact with being itself, if, before any voluntary adoption of a position, I were not already situated in an intersubjective world" (p. 355). Merleau-Ponty adopts Heidegger's view of being-there-with-others as fundamental to the human condition. However, he does so more concretely and persistently. He refers to the perception of the other's body as material, meaningful and expressive. He cites evidence from child development that infants exist in a shared world without even differentiating themselves from others—so that subjectivity is seen to be a derived and learned phenomenon, not an absolute Cartesian starting point.

In addition, Merleau-Ponty looks at the role of language in the perception of other people. Language is essentially social; it transcends the individual and it merges the perspectives of multiple speakers. He describes eloquently how dialogue can establish a shared thinking in the verbal interaction of two people:

> My thought and his are interwoven into a single fabric, my words and those of my interlocutor are called forth by the state of the discussion, and they are inserted into a shared operation of which neither of us is the creator. We have here a dual being, where the other is for me no longer a mere bit of behavior in my transcendental field, nor I in his; we are collaborators for each other in consummate reciprocity. Our perspectives merge into each other, and we co-exist through a common world. In the present dialogue, I am freed from myself, for the other person's thoughts are certainly his; they are not of my making, though I do grasp them the moment they come into being, or even anticipate them. And indeed, the objection which my interlocutor raises to what I say draws from me thoughts which I had no idea I possessed, so that at the same time that I lend him thoughts, he reciprocates by making me think too. It is only retrospectively, when I have withdrawn from the dialogue and am recalling it that I am able to reintegrate it into my life and make of it an episode in my private history. (p. 354)

Through elicitation and response, the utterances of people in dialog produce a cognitive stream that is not attributable to either speaker individually, but is a group process that only makes sense as such. This is a description of collaboration as an intersubjective form of cognition. There is a common world, in which the two personal perspectives are integrated in a single process of intersubjective meaning making—a "shared fabric." The view of an individual's contribution to the dialog is a retroactive view, the result of subsequent reflection and appropriation into ones (linguistic) self-narrative.

Merleau-Ponty's description of the intersubjective source of my own creativity is particularly striking. The other draws from me thoughts "which I had no idea I possessed." Of course, I did not "possess" such thoughts ahead of time—they emerged from the discourse. Nevertheless, they were understood by everyone as being my thoughts, from my perspective and due to my agency. Here we get a glimpse of the power of intersubjective collaboration—and of how it is systematically covered over by commonsense views, interpretations and retrospective accounts.

This model of intersubjectivity goes beyond Husserl's and Schutz' analyses of the individual's "transcendental field." It also escapes Heidegger's version of intersubjectivity as an obfuscating mass culture. Merleau-Ponty agrees that one can step back from intersubjective engagement to reflect on one's personal life, but now with positive insights about one's own thinking that would not otherwise have occurred. Finally, we have a conception of intersubjectivity that values the potential of collaboration and of our concrete joint life in a shared world. Here, intersubjectivity can be a primordial experience, which provides a foundation for individual consciousness as derivative.

In recent decades, followers of phenomenology have adopted the shift of starting point from the individual to the shared world, pioneered in Heidegger's being-there-with-others, the later Husserl's lifeworld and Merleau-Ponty's intersubjectivity. For instance, Schegloff (1991, p. 168) writes, "In Western tradition, it is the single, embodied, minded individual who constitutes the autonomous reality." He then contrasts the view of phenomenologically inspired ethnomethodology and conversation analysis to this earlier dominant cognitivist tradition: "Interaction and talk-in-interaction are structured environments for action and cognition, and they shape both the constitution of the actions and utterances needing to be 'cognized' and the contingencies for solving them." As their names suggest, ethnomethodology describes the pervasive methods that people (ethno) use for creating social order during their interactions, and conversation analysis describes the patterns of talk that people use to support intersubjective understanding of the public meaning that is thereby created in the shared world. This approach details the rich and orderly variety of mechanisms that are used in human interaction to constitute and maintain intersubjectivity.

In addition to his phenomenological roots, Merleau-Ponty appreciated the other major philosophic tradition in twentieth-century European thought, that of Hegel and Marx, to which we turn next.

The Dialectic of Intersubjectivity: Hegel and Marx

When the movement of social history became conspicuous with the American and French revolutions, the march of Napoleon and the early stirrings of the industrial working class, Hegel captured the nature of his dynamic times in his philosophy. His early lectures in particular defined a break with Kantian methodological individualism and described the social nature of man (Habermas, 1967; Hegel, 1806). This led to a philosophic approach to subjectivity contrasting to that of Husserlian phenomenology, which had remained neo-Kantian.

Until Hegel, human nature and human cognition were conceived as based in the individual person, as fully determined from birth ahistorically or universally—not dependent on one's biography or social context. The theories that minds develop, that social relations transform or that humanity evolves all came after Hegel—in process-oriented sciences inspired by his philosophy. For Freud, Marx and Darwin, to understand a psyche, a social formation or a species requires understanding the history of its development, complete with conflicts and resolutions.

Hegel elaborated a dynamic view, in which mind develops all the way from primitive sense perception to sophisticated self-consciousness and cultural worldview. In the methodological Preface to his most influential presentation of the development of mind, Hegel (1807) wrote that one must analyze a phenomenon by looking at its unity as the result of its clashing temporal appearances:

> The bud, the blossom and the fruit's fluid nature make them into moments of an organic unity within which … one is equally as necessary as the other…. The subject matter is not exhausted in its ends; rather, it is exhaustively treated while it is worked out. Nor is the result that is reached the actual whole itself; rather, *the whole is the result together with the way the result comes to be*…. What is the most difficult of all is to grasp both what unites the process and the result, and to give a full exposition of what that is. (§2 & 3, my translation and italics)

Let us see how Hegel treated interaction between two people in his famous master/slave dialectic. A person first becomes aware of himself as a particular individual at this developmental stage within Hegel's system. The analysis focuses on the interaction of people and involves them working with objects in the world. The cognitive effect (self-consciousness) is a result of the whole dynamic of the interaction, not a pre-existing causal agent within the interaction. The prototypical interaction is here that of a worker creating an artifact; the worker recognizes himself as reflected in the product that he created to meet the needs of another person:

> Work *gives form* to its object. The worker's transforming relationship toward the object is transformed into the object's form and becomes something *persisting*, because for the worker the object gains self-sufficiency. This transforming mediation—the *activity* of forming—is also the *individuality* of consciousness or the pure being-for-itself of consciousness, which in the work process now steps out of consciousness and takes on the character of persistence. The consciousness of the worker thereby arrives at a perception of the self-sufficient artifact as a perception *of his self*. (Hegel, 1807, p. 238, my translation)

Hegel shows how human consciousness emerges through productive activity in the intersubjective and physical world. The worker and the master (for whom the object is produced) are formed as such (i.e., as self-conscious individual actors) through the interaction with each other and with artifacts (tools and products of work) in the world. Hegel describes the emergence of self-consciousness from within the process of mutual recognition of self, world and other. In particular, it is the worker, who produces an artifact in the physical world at the bidding of another, who is then able to perceive his labor as externalized and made persistent in the artifact. The worker's self-consciousness emerges through his activity in the shared world, where he comes to see himself as objectified in his artifacts and through the eyes of others.

Marx (1867) builds on this analysis of social interaction. He situates Hegel's idealist analysis in the historical context of early capitalism. The artifact that is produced by the worker's labor and that externalizes his self within its social relations to other people is specified within settings of capitalist production into a commodity (an artifact produced for sale on the open market). The worker's self-consciousness is reified, alienated and fetishized because the commodity that reflects his identity is no longer his (but the capitalist's, who sells it) and because his social relations to potential users of the artifact are transformed into the abstract monetary value of the commodity. The meaning of the labor that went into forming the product's use-value undergoes multiple complex social transformations: it is externalized into an artifact; the artifact enters commodity relations and the commodity is reflected back to the worker as monetary exchange-value belonging to his boss. For Marx, individuals in capitalist society are analyzed as results of their interactions as wage laborers, owners of the means of production or consumers of commodities. He critiques the traditional notion of the abstract individual consciousness as an ideology of individualism that obscures concrete, historically specific human reality.

In his methodological *Grundrisse*, Marx (1858) identifies the interaction in which the worker exchanges his labor time for the capitalist's wages as the "cell form" for analysis. His analysis in *Capital* (1867) starts out from the simple dyadic interaction of a worker exchanging the product of his labor with another person. As his inquiry into social production in the capitalist era develops, this elemental intersubjective relation of production is mediated by its dialectical relationship to technology as the social means of production (e.g., the factory system, machinery and automation in their historical development).

Intersubjectivity in this approach of Hegel and Marx is a concrete social and historical product of human labor with material artifacts. The subjectivity of individuals is a subsequent by-product of their interactions within the shared social world. The Kantian view of the individual mind producing the world is stood on its head. Mind is seen to be a social product, and individualism is characterized as an ideology serving competitive capitalism.

In a contemporary extension of this tradition, Habermas (1971) has argued for viewing communicative action as the basis for intersubjectivity and social theory. He starts by explicitly rejecting the individualism of Kant and Husserl, which do not allow escaping from monadic subjectivity. Incorporating the linguistic turn of Wittgenstein (1953), Habermas reconstructs the possibility of moral behavior and social science from the interpersonal relationship between people engaged in communicative action. The dialectical tradition takes as its starting point the social interaction among people in place of Descartes' isolated subject. It focuses on the dynamic and conflictual mediations of this interaction within the concrete, historical world.

The Mediation of Intersubjectivity: Vygotsky

Vygotsky provides a psychology of human cognition appropriate to Marx's methodology of social science. He adopts Marx' analytic cell form: the interaction among people mediated by artifacts. For Vygotsky, the notion of artifact encompasses both tools and language. Artifacts are both physically present in the world and meaningful to people. Their meaning is not projected from individual minds, but is intersubjectively emergent from social interactions, as in the dialectical presentations of Hegel and Marx.

As discussed in the section of Investigation 15 on a post-cognitive educational paradigm, Vygotsky analyzed the genesis of the pointing gesture as an artifact whose form and meaning emerge from the interaction between multiple actors, such as an infant and its mother. The actors form an intersubjective group, whose joint attention is directed toward some intended object by the co-constructed pointing gesture. This view of intentionality as emergent in the shared world stands in sharp contrast to the rationalist assumption that individuals "have" personal mental aims which they then express in speech or action and which others may notice and interpret in their own minds. Marx, Wittgenstein and Heidegger (the primary founders of the major approaches in twentieth-century theory)—and their followers—soundly reject the cognitive picture of agency (see, e.g., Dennett, 1991; Dourish, 2001; Dreyfus, 1992; Ehn, 1988; Suchman, 2007). The rationalist, mentalist view persisted in the theories of intersubjectivity of Husserl and even Schutz, as we have seen.

Although Vygotsky was a trained psychologist and even a behaviorist during part of his career, his research agenda points toward a vision of group cognition. For instance, Vygotsky's analysis of learners' "zones of proximal development" stresses the origin of higher forms of human cognition in developmental processes involving intersubjective meaning making. In a formulation evoking Hegel, he writes of the need to analyze such developmental processes, not just learning outcomes: "The zone of proximal development defines those functions that have not yet matured but are in the process of maturation, functions that will mature tomorrow but are currently in an embryonic state. These functions could be termed the 'buds' or 'flowers' of development rather than the 'fruits' of development." He then cites a study in which children "could do only under guidance, in collaboration and in groups at the age of three-to-five years what they could do independently when they reached the age of five-to-seven years" (Vygotsky, 1930/1978, pp. 86, 87). In Vygotsky's approach, cognitive development is founded on the intersubjectivity of collaborative learning. The results of collaborative learning may later appear as individual learning through subtle processes of "internalization."

In his less quoted section on "Problems of Method," Vygotsky (1930/1978, pp. 58-75) called for a new paradigm of educational research almost a century ago. Arguing that one cannot simply look at visible post-test results of an experiment, he approvingly quoted Marx: "if the essence of objects coincided with the form of their outer manifestations, then every science would be superfluous." He then emphasized the Hegelian approach: "*To study something historically means to study it in the process of change*; that is the dialectical method's basic demand. To encompass in research the process of a given thing's development in all its phases and changes—from birth to death—fundamentally means to discover its nature, its essence." In Vygotsky's analysis based on his experiments with young children, the skills and understanding of individuals is traced back to their long-forgotten origins in intersubjective meaning making.

Vygotsky (1930/1978) outlines an intersubjective conception of the development of human cognition and collaborative learning, which treats the interaction, development and learning of small groups with artifacts in the shared world as foundational. We shall see a concrete example of this approach toward the end of this Investigation. Ones understanding of oneself, of artifacts (including representations, gestures, signs, symbols, language) and of the meaningful world is constructed primarily and originally intersubjectively, socially and culturally. The individual is a result of subsequent processes of internalization, including the transformation by young children of speech as intersubjective communication into self-talk and then into silent verbal rehearsal or thinking.

The Evolution of Intersubjectivity: Tomasello

Tomasello (2014) complements Vygotsky's dialectical psychology with a corresponding evolutionary anthropology. He offers us a theory of intersubjective intentionality based on an analysis of human evolution and how human intentionality diverged from that of other primates throughout pre-history. He complements Vygotsky's historical, developmental analysis of a child's learning with a similarly historical analysis of the development of human cognition by the species.

Under environmental pressures, humans developed increasingly complex forms of cooperative sociality (see also Seddon, 2014). Tomasello describes a two-step evolutionary sequence: *joint intentionality* followed by *collective intentionality*. At both of these transitions, a similar process took place. "A change of ecology led to some new forms of collaboration, which required for their coordination some new forms of cooperative communication, and then together these created the possibility that, during ontogeny, individuals could construct through their social interactions with others some new forms of cognitive representation, inference and self-monitoring for use in their thinking" (p. 31).

Perhaps the first step took place in the context of collaborative foraging. Early human individuals— in response to a changing feeding ecology—began to join other individuals in pairs in pursuit of shared goals, and they jointly attended to situations relevant to their common goals.[7] "Each participant in the collaboration had her own individual role and her own individual perspective on the situation as part of the interactive unit" (p. 78). Tomasello highlights this dual-level structure—*simultaneous joint participation and perspectival individuality*—as a defining structure of what he calls joint intentionality. For him, it is foundational for all subsequent manifestations of human shared intentionality. Of course, early humans had always lived in family units and small tribes (like other primates), but now they began to carry out tasks like strategic hunting in small teams as an "interactive unit."

The second step took place more recently, as agriculture and domestication of animals led to the founding of the first great civilizations. Modern humans became predominantly cultural beings by identifying with their specific cultural group and collectively creating various kinds of cultural conventions, norms and institutions (p. 80). They thus became thoroughly group-minded individuals. Tomasello argues that the development of joint and collective intentionality provided a necessary foundation for the development of human language and culture, which allowed for the escalating evolutionary emergence of modern human cognition and thinking (p. 128). This rapid form of evolution took place through historically transmitted culture (Donald, 1991;

[7] Evolutionary development of mirror neurons and increased brain structure on the biological level may have accompanied and facilitated this increased sense of mutuality on the cultural level as a competitive advantage (Gallese & Lakoff, 2005), but see also (Hickok, 2014).

2001), rather than as biological adaptation. Increasingly, our individual cognition became mediated by and derivative of group, collective, cultural and now even global cognition.

Intersubjectivity—as the recognition of other people as having the same kinds of comprehension capabilities as we do (so-called "theory of mind")—involves perspective taking, being able to view from the other person's position. For instance, to understand what someone says to me, I have to be able to understand the utterance as coming from the other person, as she might have understood it in articulating it. I also have to understand it as having been designed for me to understand it ("recipient design"). So, I have to recognize the speaker as someone who understands meaning and can create it, as well as someone who knows how I might understand what she says. This mutual or reciprocal recognition is a precondition for distinctively human communication (e.g., as evolved beyond animal vocal signaling). Intersubjectivity is a foundation for—a condition for the possibility of—modern human interaction (Duranti, 2010).

Of course, our understanding of each other is only tentative and partial. There is no possibility of absolute knowledge of other minds or of identity of mental contents, as Husserl and Schutz argued. Shared understanding is, rather, taken-for-granted, not objective. Furthermore, the sharing is generally developed only to the point necessary to maintain communication (Linell, 2014). In general, understanding is always partial and pragmatic; I only understand even my own thoughts enough to continue engaging in the current activity that involves those thoughts.

As Heidegger put it, understanding is an aspect of our being-in-the-world, of situated activity rather than of abstractly mental cognition. We understand something *as* something to the extent necessary for our dealings with it. Accordingly, our shared understanding with other people should be seen as an aspect of our being-there-with-others in the same world [Investigation 17]. We share understandings because we share one world; and we do so to the extent necessary for our care for things in the world and our concern for other people as part of our existence in the social world (with our background, our plans, our situation).

The discussion of intersubjectivity in twentieth-century philosophy and social-science theory has moved decisively away from the rationalism of Descartes and its focus on the reasoning of an individual mind. We are embodied in a shared world, and we understand ourselves, each other and our world through social interaction, gradual cognitive development and cultural transmission. Intersubjectivity can be more than just the confrontation of independent individuals. It can include the collaborative production of joint meaning in a shared world, where the interaction can result in a unity that is more than a simple aggregate of the inputs of the individuals.

The refined conceptions of shared understanding in our intersubjective world that emerge from the preceding review are suggestive for research in CSCW and CSCL. We turn now to examples of empirical studies from these fields.

Intersubjectivity in CSCW

The lead article in the CSCW journal special issue on intersubjectivity, by Tenenberg, Roth & Socha (2015), documents an instance of intersubjectivity in which there is joint attention and mutual recognition. Many of the characterizations of forms of intersubjectivity summarized above can be related to the recorded actions of software programmers Hank and Danny in that case study and to the analysis of the data by the article authors.

All of the theory sources considered in this Investigation have discussed the importance of one person seeing the other and being able to observe that they were attending to the same objects. This was a central theme in the lead article as well. The pair-programming work environment being studied was carefully structured so that the participants could see each other and could track each other's general gaze. This environment was an interesting hybrid of face-to-face and computer-mediated. In fully online alternative systems mentioned in the article, the awareness of joint attention was either supported with specific functionalities or seen to be problematic.

The article explicitly focuses on the initial alignment phase of Hank and Danny working together. Consequently, we do not get to observe much of how they subsequently proceed in accomplishing their shared work in a fully intersubjective mode. The data presented gives a glimpse into a very narrow—but critical—slice of the intersubjective experience. As the authors note, Hank and Danny are very much at home in their specific work world and only need to align around the particular task at hand. These programmers are experienced at working together in this paired manner. The physical and technical environment has been carefully set up to support their closely coupled cooperative work, and they move around within it skillfully, without displaying explicitly much of the understanding or practices that contribute to such being-there-with-others.

Paired programming—like intersubjectivity itself—can be viewed in two ways. In one (like Husserl's), there is cooperation between two subjectivities, who coordinate their actions and reciprocal understandings of each other in two parallel streams of individual cognition. Excerpts 1 and 2 in the article include division of labor, for instance where Danny will write a list on paper while Hank operates the computer. In this view, one programmer may bring in resources (knowledge, skills, processes, artifacts) that the first does not have, or the second programmer can provide an immediate check on the work accomplished by the first.

In the alternative view (like Tomasello's), the pair collaborates in a single cognitive process of jointly accomplishing the programming task. For instance, the interaction presented in Log 1 can be seen as the pair narrowing in on a relevant object together through their joint attention to a list on the screen and their interactive construction of an increasingly narrow focus within that list.

3.1 Danny: ((Just before he starts talking, Danny moves his left hand that is holding a pen so that the pen points to a specific item on a dropdown menu on the left monitor)) I bet you if

3.2 ((at apex of point, with pen tapped on screen))

3.3 ((Hank selects item on list that is four items below Danny's point, which is highlighted on the display))

3.4 Danny: you (go?) ((starts to withdraw hand))

3.5 Hank: ((Hank uses mouse to move cursor two elements higher on the list))

3.6 Danny: bidoni

3.7 Hank: ((Hank moves up two additional elements on list, stays there))

3.8 Danny: m-t-m black

Log 1. Interaction by pair-programmers.

The authors first describe the actions of the programmers: "Danny uses physical gestures and speech that complement and complete one another to direct Hank to a specific location. Hank uses the mouse for placing the cursor preparatory to acting with it, which, in its visibility to Danny takes a role in the 'conversation' that the two are having concerning the specific location of the next operation." Then the authors summarize the interaction as follows: "They thus combine a variety of semiotic resources to give this fragment its orderly, sequential character." What they call the programmers' "conversation" (including words, cursor movements, pointing gestures and mutual bodily visibility) is in fact a single, well-ordered achievement. It is irrelevant which programmer introduced which resource. All the resources received their meaning from the unfolding joint process of locating the cursor on a particular font name so that the team could work on that object. The actions of the two programmers form a single orderly sequence.

In the analysis of this work as a collaboration, the two programmers are seen to be checking—or grounding (Clark & Brennan, 1991)—their understanding of each other through their utterances, repairs, gestures and gazes. This reciprocal testing of interlocutors' understandings corresponds to the mutual reciprocity of knowledge in some of the theories of intersubjectivity reviewed above. Certainly, Husserl and

Schutz, with their orientation to individual consciousnesses, relied heavily on one subject's knowledge that the other knows that the first knows that…. Even Tomasello focuses on the recursive recognition of other minds as sentient and perspectival. While Tomasello is persuasive that the evolution of this capability of recursive recognition to arbitrary levels was a necessary evolutionary precondition for modern human cognition and collaboration, that does not mean that we must always engage in some sort of mental recognition that you understand that I understand, etc. There may be occasions when this is indeed necessary, but only then does it actually have to be carried out. Furthermore, we have the ability to respond to questioning by making retroactive statements of mutual recognition to arbitrary levels of recursion. However, this need not enter into most activities of joint understanding. Such mutual recognition is already implicit in the fact of joint understanding. It is taken for granted in Heidegger's being-there-with-others, in which we care for each other as human, or in Merleau-Ponty's gaze, in which we see the body of the other as another human perspective on our shared world.

In his recommendations for social-science analysis, Garfinkel (1967) noted that common ground is established by the methodical ways in which things are said, not by a process of verifying agreement of the sets of presumed mental contents stored in the heads of the speaker and of the hearer:

> For the conduct of their everyday affairs, persons take for granted that what is said will be made out according to methods that the parties use to make out what they are saying for its clear, consistent, coherent, understandable, or planful character, i.e., as subject to some rule's jurisdiction—in a word as rational. To see the "sense" of what is said is to accord to what was said its character "as a rule." "Shared agreement" refers to various social methods for accomplishing the member's recognition that something was said-according-to-a-rule and not the demonstrable matching of substantive matters. The appropriate image of a common understanding is therefore an operation rather than a common intersection of overlapping sets. (p. 30)

The authors of the lead article have gone to pains to avoid mentalist explanations. They formulate their discussion of aligning visual fields in terms of the methodical ways of establishing joint attention to a shared object rather than as checking that one subject knows that the other is looking at the object, and the other knows that the first knows that, and so on. The establishment of joint attention—so necessary for collaboration—entails that the people involved are looking at the same object *together*. They do not just happen to be both individually oriented to the object, but are oriented toward it in a coordinated way. They do not have to be separately aware of the assumed recursive mutuality of this relationship—unless there is some kind of breakdown that needs to be repaired by checking verbally on the mutuality of gaze to some recursive depth. A contribution of the lead article analysis is to explicate the need to support the participants' operations of maintaining awareness of the mutuality of their joint attention and to describe their methods of doing so in their hybrid environment.

Just as there is an ambiguity to the method of paired programming between cooperation (with division of labor) and collaboration (working together on each step, although possibly from different perspectives or with different resources), so there is an ambiguity to the transcript in Log 1. While we have viewed the interaction there as a single, coherent, meaningful achievement, it could also be viewed in terms of the distinct actions of two individual subjects. One could speculate that Danny had himself identified the item in the list on the computer screen from the start by tapping on it with his pen. Then Hank followed Danny's guiding gestures to eventually recognize the same item by highlighting it with his cursor. This is a pervasive ambiguity in the analysis of CSCW data. To decide in favor of an analysis that treats the group as the primary agent or one that focuses on the contributions of individuals generally requires detailed interactional data, which is rarely available to researchers. For instance, if the transcript did not include Danny's bodily gestures and Hank's computer actions in addition to the spoken discourse, it would be impossible to analyze the identification of the font as a joint achievement.

The alignment phase involves a transition from individual cognition to intersubjective cognition. It therefore contains elements of each and can be analyzed at either the individual or group unit of analysis. At the individual level, it appears that subjects are monitoring each other's gaze or focus of attention. Here is where the reciprocal and recursive recognition come in and the conception of communicative signals being exchanged. Especially in the case of dyads, it is tempting to analyze individual intentionality and agency in a traditional, individualistic way; in somewhat larger groups, the interaction is often harder to attribute to individuals as the discussion builds on individual utterances in complex ways and takes twists that no one participant could have planned. At the group level of description, the group is beginning to act as a unity, creating social order and joint meaning in a shared world—not through independent acts of the individual participants, but through the interaction of the group.

The ambiguity is important. The point is not so much to always opt for an individual or a group focus, but to recognize their intertwining: that the individual is a social product, but also that the intersubjective has the individual at its poles. Sometimes one unit of analysis is more useful than the other. Efforts at alignment, in particular, involve a transition from multiple individual cognitions to unified group cognition. Philosophies of dialogicality have long tried to maintain this balance of what Tomasello calls joint intentionality with individual perspectives, which is not well supported by our inherited conceptualizations (Rommetveit, 2003; Wertsch, 1991). Interaction analysis—as carried out in the lead article—has shown us how to analyze the displayed utterances of individuals as part of intersubjective processes of group meaning making and social-order construction, without hypothesizing hidden mental phenomena (Schegloff, 1991).

To understand we-awareness or intersubjectivity once a team has come into alignment and is working smoothly together, it would be useful to analyze excerpts of interaction in later phases with the same kind of detail provided for the alignment phase in the lead article. Fuller examples of completely online group work would also be relevant to CSCW. The authors note a paucity of appropriate, detailed data about computer-mediated CSCW interactions on work like paired programming using different mediating technologies. In addition, we might add, there is little data reported about how people first learn to interact skillfully within such contexts. For a suggestion of how intersubjectivity might be analyzed and supported in more contexts, we turn to CSCL.

Intersubjectivity in CSCL

The relation of CSCW to CSCL has not been widely noted or clearly articulated. Both involve computer support for people interacting. While CSCW has the advantage of studying people who are expert at their work and experienced at working together, CSCL has the advantage of observing how such expertise and such interaction between people is originally constituted and learned. CSCL education can prepare students for careers in CSCW workplaces, and CSCW can display domain-related practices for adoption in CSCL curricula. The two fields share an interest in how individual and intersubjective cognition complement each other and how computer-support artifacts or environments can mediate between them.

We will now review a specific research agenda that explores the nature of intersubjectivity in a variety of small-group math-education settings. We will present examples of intersubjective knowledge building under several diverse, but typical learning conditions, involving computer mediation.

Based on research in CSCW and CSCL, Stahl (2006) proposes a form of intersubjectivity called *group cognition*. Group cognition can be thought of as a form of intersubjectivity that goes beyond the mutual recognition of individual minds in Husserl and the recursive thou-relationship of Schutz to a being-there-with-others that Heidegger and Merleau-Ponty briefly hint at. Its analysis is based on the social-historical-cultural approach of Hegel, Marx and Vygotsky. It is a developed form of Tomasello's joint intentionality with individual perspectives. Group cognition is a vision of intersubjectivity for CSCW and CSCL, which exceeds the accomplishments of individual cognition within group efforts, especially in online settings.

In group cognition, multiple people participate in coherent interactions that achieve cognitive accomplishments which are best analyzed at least in part at the group unit, rather than attributing contributions and agency entirely to individual minds. When a number of people are involved in group-cognitive processes or activities, their individual utterances or actions are taken as merged in a single cognitive system, which is distributed across the people and the artifacts that are involved (Hutchins, 1996). Ideas, practices, habits and traditions from the larger culture are also brought in, so that the group cognition mediates between individual and community levels of description (Stahl, 2013, Ch. 8).

The original elaboration of the notion of group cognition emerged from a series of studies of software environments to support perspectives, negotiation and group formation in specific workplace and school settings (Stahl, 2006, e.g., Ch. 3, 6, 8). It provided, for instance, a detailed example of group cognition, in which a face-to-face student group co-constructed the applicability of a scientific representational artifact in an educational computer simulation in 1998 (Ch. 12 & 13). However, the collection of studies also acknowledged that the vision of group cognition as an effective form of collaborative learning is rarely achieved in practice. Furthermore, it noted the difficulty of finding or collecting data that is adequate for establishing and analyzing group cognition, let alone for observing the mediation across units of analysis.

Later (from 2002-2015), the Virtual Math Teams (VMT) system was developed as a test ground for studying group cognition. VMT is a collaboration environment for mathematical problem solving by online small groups of students. Reports on pedagogical and methodological issues in VMT (Stahl, 2009) include analysis of a text chat in which several online students solved a challenging word problem collaboratively that none could solve individually (Ch. 5). The analysis argues that their chat could be viewed as a group-cognitive accomplishment, integrating a chain of interactive responses similar to a solution that could have been stated by one person, but here involving the whole group as the problem-solving agent. Another case study (Ch. 7) discusses how three students working online in VMT with a shared graphics whiteboard maintain joint attention to geometric details and organize their graphical, symbolic and narrative interactions to solve an intricate problem in combinatorics collaboratively.

More recently, the VMT environment was extended with a custom multi-user version of GeoGebra, an application for dynamic geometry. A stimulating problem often given to people once they become comfortable with dynamic geometry is that of constructing inscribed triangles that behave like a given pair of inscribed triangles. (See the instructions and inscribed triangles ABC/DEF in Figure 1.) This is a difficult task even for adults who enjoy mathematics. The VMT research team looked closely at the logs of a group of three 14-year-old girls who succeeded with this problem in less than an hour. None of the students had studied geometry before joining an after-school math club as part of the research project; they spent four hours working together on collaborative dynamic geometry before this session.

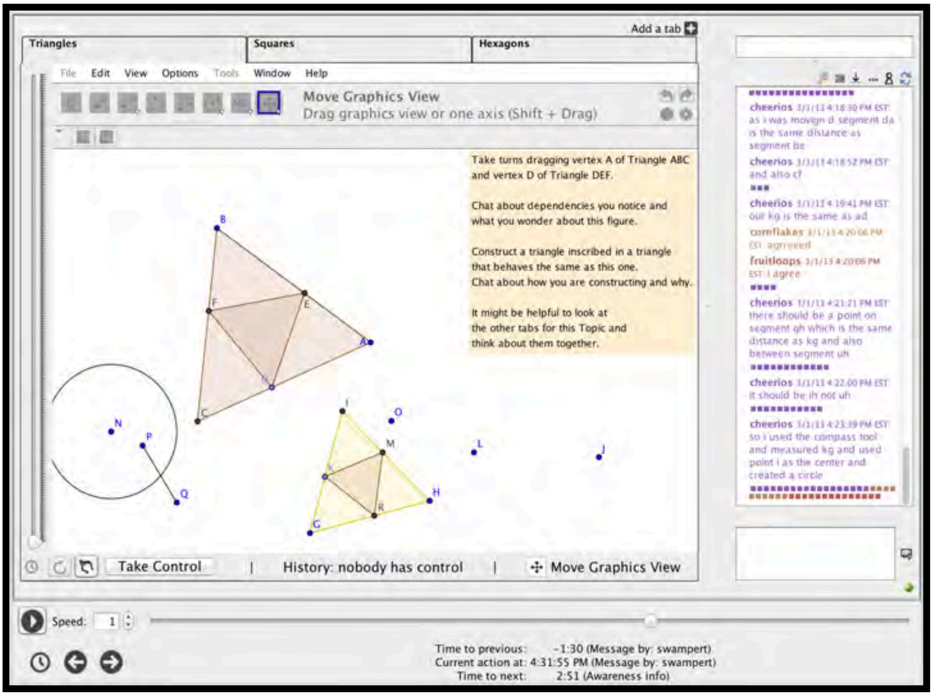

Figure 1. The state of the inscribed-triangles construction after Fruitloops finished triangle KMR inscribed in GHI.

The analysis of the team's work concludes that the students' success was an instance of group cognition (Stahl, 2013, Ch. 7.3). None of the students could construct the triangle configuration themselves, and the process of construction involved all three exploring, planning and carrying out the construction. Each of the three girls displays a different characteristic behavior pattern throughout their work in the eight hour-long sessions of our study. Yet, the team is impressively collaborative. This illustrates nicely the notion of individual perspectives within intersubjective group interaction.

What is particularly striking in the team's successful construction of the inscribed triangles is that on first appearance it seems like the team's insightful and skilled work is actually done primarily by the student who until then had seemed the least insightful and skilled. If one just looks at the chat postings (see panel in the right side of Figure 1), Cheerios does all the talking and Fruitloops (who is usually the most reflective and insightful) and Cornflakes (who explores the technology and often shows the others how to create geometric objects) simply register passive agreement. However, the actual GeoGebra construction actions tell a far more nuanced story. First, for most of the hour, each of the three students in the "Cereal Team" takes extended turns exploring the given example of inscribed triangles by dragging the vertices to discover dependencies in the construction that dynamically maintain the invariances of equilateral triangles. The dragging of figures is displayed simultaneously on each student's computer. Only one person at a time can create or drag geometric objects, in order to maintain joint attention by everyone to a single, shared sequence of actions.

Cheerios observes Fruitloops experimenting with the use of the GeoGebra compass tool just before Cheerios takes control and makes her discovery. Cheerios continues to manipulate Fruitloops' construction, involving a circle whose radius was constructed with the compass tool to be dependent on the length of a line segment. Then Cheerios very carefully drags points on the original inscribed-triangle figure to discover how segments BE and CF are dependent upon the length of segment AD, refining prior movements by the other students. The dynamic relationship between the side lengths becomes visually salient as she increases the size of the triangles or their orientation and as she drags point D along side AC.

Cheerios has a sense that the compass tool should be used to measure segment KG, but she does not quite understand how to make use of that tool. Following Fruitloops' example, Cheerios uses the compass to draw a circle around point I, whose radius equals length GK (see Figure 2, left). However, she is unable to further implement the plan she has already projected in chat.

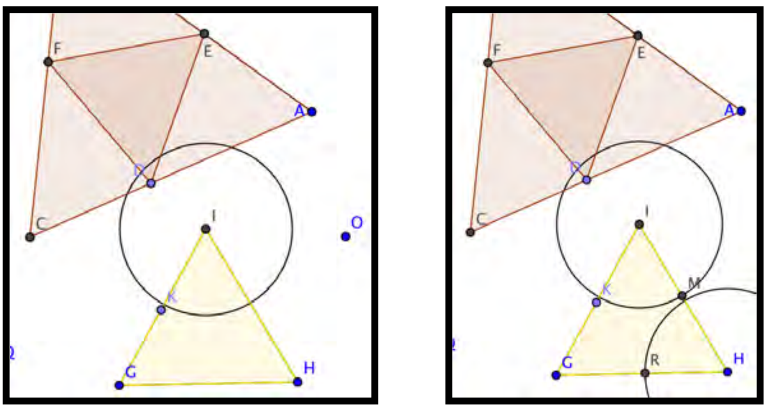

Figure 2. The state of the construction after Cheerios finished (left) and after Cornflakes finished (right).

Next, Cornflakes takes control of the construction, places a point, M, where Cheerios' circle intersects side HI and then repeats the process with the compass to construct another point, R, on the third side of the exterior triangle (see Figure 2, right).

Fruitloops then takes control and uses the polygon tool to construct a shaded interior triangle, KMR, connecting Cornflakes' three points on the sides of the exterior triangle (see Figure 2). She then conducts a drag test, dragging points on each of the new triangles to confirm that they remain equilateral and inscribed dynamically, just like the example figure. At that point, the students have been working in the room for over an hour and end their session, having succeeded as a team.

The VMT software is fully instrumented, so that researchers can obtain detailed logs and even replay the sessions (as shown in Figure 2, a screen image from the replayer) to see precisely what the students all saw on their screens. Of course, as Schutz pointed out, researchers have a reflective relationship to the interaction, which is quite different from the engagement of the students. The intersubjectivity of the students, when things are functioning optimally, can be that of group cognition, where they act as one subject, constructing shared meaning through their interaction. The intersubjectivity of the researchers with the students involves systematic (methodical, self-conscious, research-driven, theory-laden) efforts to understand the meanings previously created by the students, based on a culture and world partially shared by the students and researchers.

Intersubjectivity as Group Cognition

The kind of data generated by teams of students using VMT can support detailed research into the nature of interaction and intersubjectivity in CSCW and CSCL situations. For instance, the VMT research team has now analyzed all eight hours of the Cereal Team's interaction (Stahl, 2016). In particular, the analysis tracks their enactment and acquisition of various member methods or group practices. It documents how the students form into an effective team and how they align and develop joint attention. By adopting specific sequences of group practices, the team learns how to collaborate, to manipulate technological affordances, to engage in collaborative dynamic-geometry problem solving and to enter into mathematical discourse. One can see, displayed in the team interaction, group cognition in action as a specific form of intersubjectivity.

We see the potential productivity of collaboration in the way that the three students, participating from within their personal zones of proximal development, bring different resources to the interaction. Further, the interaction itself—including the reactions of the GeoGebra application to student attempts at geometric construction—elicits, as Merleau-Ponty put it, "thoughts which I had no idea I possessed." Ideas, skills and approaches from different sources mix and spontaneously generate new, shared knowledge through the interaction itself and its internal logic or implicit connotations. Collaborative learning may be guided through reflection by the participants and through feedback from the problem-solving process itself. For instance, observation of the results of various people's efforts at geometric manipulations and constructions may lead to the discovery of solutions that cannot be attributed to any one of the participant's minds or even to a simple aggregation of their individual contributions. The dynamic, over-determined behavior of their joint geometric-construction moves in their shared online world contributes to the unfolding of a solution path as well. The VMT environment incorporating its multi-user version of dynamic geometry provides visual feedback to construction or dragging actions, adding a computer-supported dimension to what Schön (1992) calls the back-talk of the materials of the (problem-solution) design situation.

In the Cereal Team's work, we see multiple instances of one student contributing a skill or insight from their individual perspective or developmental zone into the group work—usually in response to what another student did or tried to do. The other students learn from this—often from just one occurrence, where the contribution is discussed and consequently adopted by the team as a group practice. Subsequently, another student brings the newly learned skill into the group work, and it is accepted without comment. In this way, first, the group learns a skill or insight and through that, each of the other individuals learns it. For instance, in the session just described, it took each of the three students doing some of the necessary actions to construct the inscribed triangles. However, in their next session, all three students very clearly knew how to carry out all those actions when the group worked on a related challenge of constructing inscribed squares.

In the longitudinal developmental trajectory of the Cereal Team (followed in detail in Stahl, 2016), as the team first learns to collaborate online and to engage in dynamic geometry, we can observe the reciprocal interpenetration of individual and collective understanding in the group-cognition form of intersubjectivity. We see what our review of theories of intersubjectivity characterized as: simultaneous joint participation and perspectival individuality, as well as joint attention, shared meaning making, group agency and being-there-with-others in a shared world.

The Cereal Team took up in their discourse mathematical terms like "constraint" and "dependency," which were introduced in their session instructions. The choice of classical geometry problems and the wording of their presentation to the students guided the student exploration and discourse, mediating the interaction with resources from the mathematical community. By responding to the cues in the instructions and incorporating these technical terms in their discourse with each other, the students gradually developed new conceptions. At first not understanding the terms at all, they passed through everyday uses of them to more rigorous mathematical statements—in a process recalling Vygotsky (1934/1986). The transitions in individual and group understanding of the role of dependencies in dynamic geometry can be tracked in the logs of their interaction (Stahl, 2016).

While all the reviewed theories of intersubjectivity noted the important role of language, Vygotsky is especially clear about the mediation of language—both spoken and silently thought—in how we understand each other and our shared world. Heidegger's later work (e.g., 1959/1971) also emphasizes how language can be seen as a source of meaning making—most visibly in poetry. For him, "speech speaks" (through us) and we live in language as the "house of being." As Tomasello (2014) notes, the cultural richness of spoken language incorporates eons of human shared experiences. In the mixing pot of group discourse, phrases evoke each other and thereby generate creative ideas.

Of course, competent language users are needed to speak and understand the phrases. However, the source of the creative generation and the deductive flow can be analyzed in terms of the meanings sedimented in the phrases, rather than being attributed to rational motives in the minds of individual participants. Group cognition and its associated intersubjectivity can be conceived in primarily linguistic, rather than mental, terms (as recommended by Habermas, 1971/2001). Its intentionality is not that of some kind of group mind or even primarily of the minds of the individual participants, but of the intersubjectively shared discourse and the historically mediated, referred intentionality of a culture, expressed in its passed-down meanings. That is why a goal of math education is to involve students in math discourse and collaborative exploration.

Group cognition is a form of intersubjectivity, in which the words and actions of group members are aligned in a coherent unity, which can be analyzed as a semantic (meaning-making) or cognitive (symbol-manipulating) system in its own right. This vision of a potentially powerful form of group intersubjectivity can inspire and guide the design of supportive technology and pedagogy in CSCW and CSCL, as it has done in the VMT project (Stahl, 2006; 2009; 2013; 2016).

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13. Constituting Group Cognition

Abstract: Cognition is no longer confined to the solitary musings of an armchair philosopher, but takes place, for instance, in problem-solving efforts of teams of people distributed around the world and involving various artifacts. The study of such cognition can unfold at multiple units of analysis. In this Investigation, three cases of problem solving by virtual math teams demonstrate the mix of individual, group and social levels of cognition. They show how a resource like a mathematical topic can bridge the different levels. Focusing on the under-researched phenomena of group cognition, the presentation highlights three pre-conditions for the constitution of group cognition: longer sequences of responses, persistent co-attention and shared understanding. Together, these structure a virtual analog of physical embodiment: being-virtually-there-together, where what is virtually there is understood as co-experienced.

Keywords. Group cognition, longer sequences, response pairs, persistent co-attention, shared understanding, embodiment, co-experience.

Cognition at Multiple Levels

There is a venerable tradition in philosophy that cognition is a mysterious faculty of individual human beings. Increasingly since the late 19th century, it has become clear that even when thoughts appear to be expressed by an individual, they are the product of more complex factors. Cognitive abilities and perspectives develop over time through one's embeddedness in a physical, social, cultural and historical world. Thinking is closely related to speaking, a form of communication with others. Particularly in our technological world, thinking is mediated by a broad variety of artifacts and by other features of the context in which we are situated.

Rather than thinking about thinking, I try to explore cognition by generating data in which one can observe cognitive processes at work (Stahl, 2006; 2009; 2013; 2016). I do this by having small groups of students collaborate on mathematical problems in a computer-mediated setting, where their whole interaction can be captured. The motivation for this approach is the theory of Vygotsky (1930/1978), the socio-cultural psychologist who proposed that higher-level human mental abilities are acquired first in small-group interactions. In exploring such group cognition, I have found that there is a rich interplay of processes at individual, small-group and community levels of cognitive processing.

In the following, I will summarize three case studies of online collaborative problem solving in order to illustrate how cognitive processes at multiple levels can work together. (1) In the first case, two students solve a high-school math problem that has stumped them for some time. The problem-solving steps the dyad goes through as a team are typical for how proficient students solve problems individually. In the discourse captured in this case, one can see how the *group* integrates contributions from the two *individual* participants to accomplish a task in accordance with *community* standards of practice—illustrating the productive interplay between cognitive levels. The sequence of ten discourse moves by the group details their extended *sequential approach* to the problem. (2) In the second study, three students develop techniques for helping each other to see what they are seeing in the diagram they have drawn for a math problem. This *persistent co-attention* to a shared object of analysis allows the team to solve their problem as a group. (3) Similarly in the third example, the students are able to work together because they effectively manage their *shared understanding* of the problem.

I propose that it is often fruitful to analyze cognition on multiple levels and that the processes at the different levels work together. A variety of *interactional resources* are typically at work bridging the levels. In the three illustrative case studies, topics in high-school mathematics centrally figure as resources that bring together individual, small-group and community cognitive processes.

Virtual Math Teams

The study of group cognition requires careful review and analysis of all the interaction within a group during the achievement of a cognitively significant task, such as solving a challenging problem. I have arranged for this by designing an online software environment in which several people can meet and interact effectively to solve math problems. This Virtual Math Teams (VMT) environment supports synchronous text chat and a shared whiteboard for drawing figures (Stahl, 2009). During the project, it was expanded to incorporate a multi-user version of dynamic geometry, in which geometric figures can be interactively constructed and dynamically dragged (Stahl, 2013). The software is instrumented to capture all interaction and to allow it to be displayed, replayed and analyzed. This avoids the many problems of audio and video recording in classrooms. Students communicate online, avoiding the interpretational issues of eye gaze, bodily gesture and vocal intonation. When possible, groups are composed of students who do not know each other outside of the online setting, so that researchers reviewing a record of interaction can know everything about the participants and their background knowledge that the participants know about each other. Since group cognition is defined as consisting of those knowledge-building or problem-solving processes that take place in the group interaction (Stahl, 2006), the VMT environment can capture a complete history of group-cognitive events.

When a group enters the VMT environment, it is presented with a challenging math problem, designed to guide the group interaction in an academically productive direction. The problem acts as a resource for the group. The group must interpret the problem statement, elaborate the way in which it wants to conceive the problem and determine how to proceed. A math problem can serve as an effective interactional resource for bridging across cognitive levels. Typically, it introduces content—definitions, elements, procedures, principles, practices, proposals, theorems, questions—from the cultural traditions of mathematics and from school curriculum. In so doing, it recalls or stimulates individual cognitive responses—memories, skills, knowledge, calculations, deductions. It is then up to the group interaction to bring these together, to organize the individual contributions as they unfold in the on-going interaction in order to achieve the goals called for by the community, institutional, disciplinary and historical sources. In this way, the group interaction may play a central role in the multi-level cognition, interpreting, enacting and integrating elements from the other levels, producing a unified cognitive result and thereby providing a group experience that can subsequently lead to community practice or individual skill.

Constructing Diamonds

Cognition is neither a unitary phenomenon nor a temporally fixed one. Hegel described the logical stages he thought were involved in the development of cognition in his *Phenomenology of Mind* (1807/1967). Vygotsky explored the development of a person's cognition through psychological experiments reported in *Mind in Society* (1930/1978), emphasizing the priority of inter-subjective group cognition:

> Every function in the child's cultural development appears twice: first, on the social level, and later, on the individual level; first, between people (*interpsychological*), and then *inside* the child (*intrapsychological*). This applies equally to voluntary attention, to logical memory, and to the formation of concepts. All the higher [human mental] functions originate as actual relations between human individuals. (p. 57)

Research on computer-supported collaborative learning (CSCL) (Stahl, Koschmann & Suthers, 2013) can make visible the development and the unfolding of cognitive functions in small groups, shedding light on the less visible processes that can subsequently be carried out by people individually or "internally." A research method for undertaking such analysis is suggested by the field of conversation analysis (CA)

(Sacks, 1965/1995). CA was inspired by ethnomethodology, a sociological approach focused on describing the "work" that people typically do in interactions with others to establish social order and to construct meaning (Garfinkel, 1967). CA applies this approach to analyzing everyday conversation. A central finding of CA is that the work of conversation is accomplished through the sequential construction of "adjacency pairs," short sequences in which one person's utterance elicits a response in the form of a following utterance by an interlocutor—for instance a question-answer pair. In looking at examples of mathematical problem solving by groups, we are more interested in "longer sequences," in which a series of adjacency pairs are constructed to accomplish the larger cognitive goal.

Longer sequences have only been suggested in CA (Sacks, 1965/1995, II p. 354; Schegloff, 2007, pp. 12, 213), not actually analyzed. In the final excerpt from a VMT interaction among three students, I analyzed their successful problem-solving effort as a longer sequence, consisting of ten discourse moves, each linguistically organized as an adjacency pair (Stahl, 2011) [Investigation 25]. I treated their four-hour-long online interaction in terms of a temporal hierarchy of: a group event, four scheduled sessions, several conversational topics, many discourse moves, adjacency pairs, textual utterances and indexical references [Investigation 24]. In the first session, the students had been asked to work on a topic in mathematical combinatorics, determining the number of squares and composite sticks needed to build a stair-step pattern at different stages of growth. By the fourth session, the students had set themselves the topic of analyzing a diamond pattern, illustrated by them at stages n=2 and n=3 in the screen image of the VMT software interface in Figure 1.

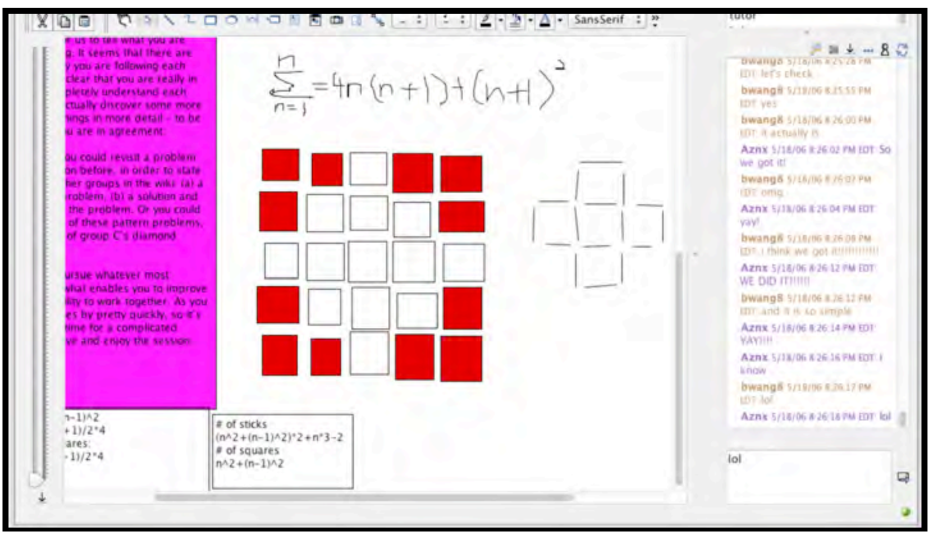

Figure 1. Discussion and drawings of diamond pattern.

In their final conversational topic, two students with login names of Bwang and Aznx decide to try again to solve this problem, despite not being able to do so for the past two hours and despite the fact that their scheduled online time is already over. In the course of ten minutes, 100 chat lines of text are posted. The analysis of these chat lines highlights ten adjacency pairs, which were central to this discourse. Each adjacency pair is listed in Log 1, under an added descriptive heading. This selection from the interaction should give a sense of the problem-solving process—see Investigation 25 for a more detailed analysis.

Move 1. Open the topic
Bwang: i think we are very close to solving the problem here
Aznx: We can solve on that topic.

Move 2. Decide to start
Bwang: well do you want to solve the problem
Aznx: Alright.

Move 3. Pick an approach
Aznx: How do you want to approach it?
Bwang: 1st level have 1*4 … 4th level have (1+3+5+7)*4

Move 4. Identify the pattern
Aznx: So it's a pattern of +2s?
Bwang: yes

Move 5. Seek the equation
Bwang: what is it
Aznx: n^2 … or (n/2)^2

Move 6. Negotiate the solution
Aznx: its n^2
Bwang: so that's wrong

Move 7. Check cases
Aznx: would be 4n^2
Bwang: it actually is

Move 8. Celebrate the solution
Bwang: i think we got it!!!!!!!!!!!!
Aznx: WE DID IT!!!!!!

Move 9. Present a formal solution
Aznx: So you're putting it in the wiki, right?
Bwang: yes

Move 10. Close

Aznx: we should keep in touch
Bwang: yeah

Log 1. Ten moves of the problem-solving topic.

There are several things to note here:

Most importantly, the sequence of identified moves is strikingly similar to how an experienced math problem solver might approach the topic individually, as described at a particular granularity.

The two students take turns contributing to the shared topic. The group direction is not set by either individual, but results from their interaction.

Most opening utterances solicit a response, often in the explicit form of a question, and they always await a response.

Each move is a situated response to the current state of the students' understanding of the topic as expressed in the discourse—rather than some kind of logical progression following a plan based on anything like a goal-subgoal hierarchy (Suchman, 2007).

The focus of the group discourse moves is on the sharing, negotiation and agreement about their progress, rather than on details of mathematical facts or computations.

The math content is handled by the individuals and contributed by them into the collaborative setting, for instance in move #3 or #5.

The temporal structure of topics, moves and adjacency pairs is not imposed by the analyst, but is projected in the remarks of the participants as integral to how they sense for themselves what they are doing and proceed.

If one follows the development of the students' understanding in their postings across the four sessions, one is struck by changing roles and confidence levels, as well as by their mastery of practices that one or the other introduced into the group. It is quite plausible that over time the lessons acquired in their collaborative interactions will become manifested in their individual cognitive skills. The longer sequences of argumentation or problem solving become "internalized" (as Vygotsky called it) or adopted as cognitive practices of individuals. The power of collaborative learning is partially to bring together multiple perspectives, which can be debated, negotiated, synthesized, contextualized, structured and refined. However, another advantage is to extend the cognitive effort into *longer sequences* of argumentation through the stimulation and enjoyment of productive social interaction, increasing the time-on-task as needed to solve challenging problems. Thus, groups can achieve cognitive accomplishments that their members cannot—and the members can learn from these achievements.

Visualizing Hexagons

Elsewhere, we have analyzed in some detail the intimate coordination of visual, narrative and symbolic activity involving the text-chat and shared whiteboard in VMT sessions [Investigation 12]. Here, we want to bring out the importance of literally looking at some mathematical object together in order to share the visual experience and to relate to—to "intend" or to "be at"—the entity together. People often use the expression "I do not see what you mean" in the metaphorical sense of not understanding what someone else is saying. In our second case study, we often encounter the expression used literally for not being able to visually perceive a graphical object, at least not being able to see it in the way that the speaker apparently sees it.

While empiricist philosophy refers to people taking in uninterpreted sense data much like arrays of computer pixels, post-cognitive philosophy emphasizes the phenomenon of "seeing as." Wittgenstein notes that one immediately sees a wireframe drawing of a cube not as a set of lines, but as a cube oriented either one way or another (1953, §177). For Heidegger, seeing things as already meaningful is not the result of cognitive interpretation, but the precondition of being able to explicate that meaning further in understanding (1927/1996, pp. 139f). For collaborative problem solving and mathematical deduction, it is clearly important that the participants see the visual mathematical objects as the same, in the same way. This seems to be an issue repeatedly in the online session excerpted in Log 2, involving three high school students with login handles of Jason, Qwertyuiop and 137 [Investigation 17].

705	19:15:08	137	So do you want to first calculate the number of triangles in a hexagonal array?
706	19:15:45	qwertyuiop	What's the shape of the array? a hexagon?
707	19:16:02	137	Ya.
708	19:16:15	qwertyuiop	ok...
709	19:16:41	Jason	wait-- can someone highlight the hexagonal array on the diagram? i don't really see what you mean...
710	19:17:30	Jason	hmm.. okay
711	19:17:43	qwertyuiop	oops
712	19:17:44	Jason	so it has at least 6 triangles?
713	19:17:58	Jason	in this, for instance

Log 2. Seeing a hexagonal array collaboratively.

Student 137 proposes a mathematical task for the group in line 705 of Log 2. This is the first time that the term, "hexagonal array," has been used. Coined in this posting, the term will become sedimented (Husserl, 1936/1989, p. 164) as a mathematical object for the group as the discourse continues. However, at this point it is problematic for both Qwertyuiop and Jason. In line 706, Qwertyuiop poses a question for clarification and receives an affirmative, but minimal response. Jason, unsatisfied with the response, escalates the clarification request by asking for help in seeing the diagram in the whiteboard *as* a "hexagonal array," so he can see it *as* 137 sees it. Between Jason's request in line 709 and acceptance in line 710, Qwertyuiop and 137 work together to add lines outlining a large hexagon in the triangular array. Demonstrating his ability to now see the hexagons, Jason thereupon proceeds with the mathematical work, which he had halted in the beginning of line 709 in order to keep the group aligned. Jason tentatively proposes that every hexagon "has at least 6 triangles" and he makes this visible to everyone by pointing to an illustrative small hexagon from the chat posting, using the VMT graphical pointing tool. Later, the students take turns using these group-defined methods of supporting shared vision and attention: using colored lines and the pointing tool, as seen in Figure 2.

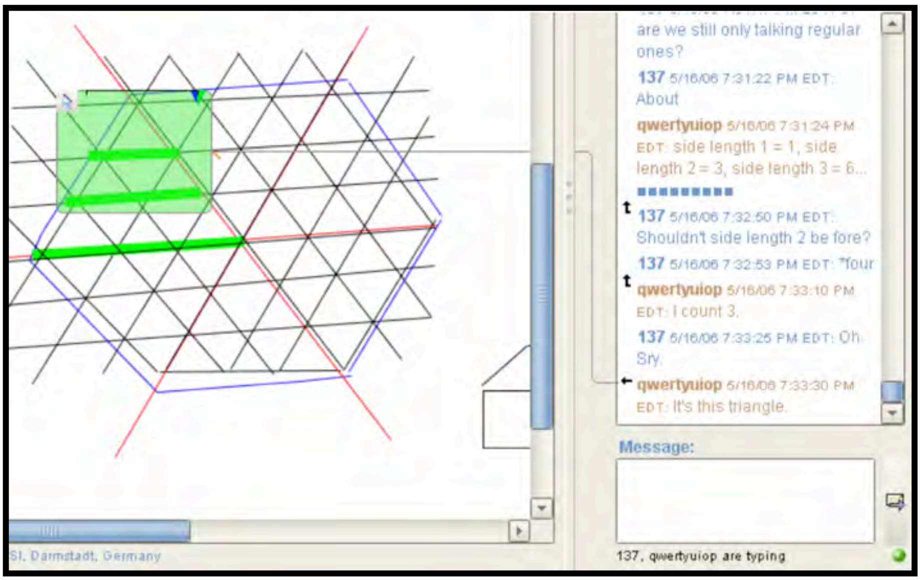

Figure 2. Discussion and drawing of hexagon grid.

Jason dramatically halted group work with his "wait." For him, it was impossible to continue until everyone could see the same thing in the way that 137 saw it. During this session, the students taught each other how to change the color and thickness of lines they constructed in the shared whiteboard. These were affordances of the VMT software, but the students had to learn how to use the features and they developed certain shared group practices of using colored lines to outline, highlight and draw attention to specific elements of the hexagonal grid. For instance, in Figure 2, blue lines outline a hexagon of side-length 3; red lines divide that hexagon into six symmetric triangles; thick green lines pick out the three horizontal lines of length 1, 2 and 3 in one of the triangles; and the VMT pointing tool focuses attention on that triangle.

There are many ways to count the number of unit sticks in the large hexagon. In order to count them as a group, everyone's attention much be focused on the same elements, such as the green horizontals. Then it is possible for each participant to count that subset visually: 1+2+3=6. Through similar shared attention to structural elements of the hexagon, all the group members know that there are three such arrays of lines like the green ones at different orientations in each of the six triangles. They can also see how this array of lines will increase as the hexagon itself progresses to successively longer side-lengths. The achievement of the necessary *persistent co-attention* to construct and to follow this complicated analysis was the result of subtle interactions and the development of shared practices within the group.

Inscribing Triangles

Our final case involves a group of three middle-school students given a topic in dynamic geometry (Stahl, 2013, Section 7.3). The students have not yet had a course in geometry, but have already spent four hours together in a version of VMT that incorporates interactive, multi-user support for dynamic geometry. In this topic, the students are given constructions of an equilateral triangle inscribed inside another equilateral triangle and a square inscribed inside another square (see Figure 3). In dynamic geometry, a student can drag one point of a figure like the inscribed squares and all the other points and lines will move accordingly, maintaining the geometric relationships or dependencies that have been built into the construction of the figure. In previous sessions, the students had learned the dynamic-geometry equivalent of Euclid's first two propositions: the construction of an equilateral triangle (using software tools equivalent to a straight edge and compass) and the copying of a line-segment length.

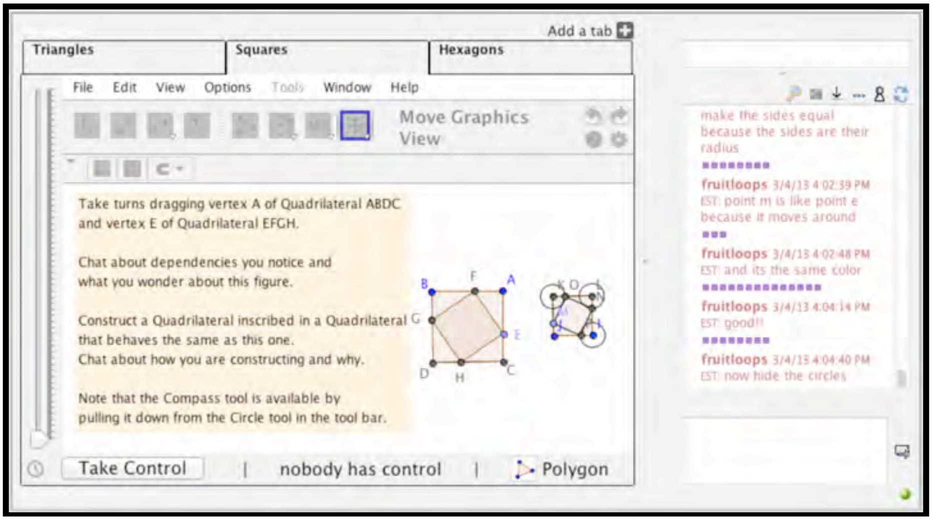

Figure 3. Discussion and constructions of inscribed squares.

In their fifth session, the three students took turns dragging points of the equilateral triangles and discussing the dependencies that were maintained. Then they tried to duplicate the given figure and to build in the relevant dependencies. For instance, the dependency defining the equilateral character of the outer triangle is that the lengths of the second and third sides must always be the same as the length of the base, even when the endpoints of the base segment are dragged, changing its length. Euclid's construction maintains this dependency because the lengths of all three sides are radii of circles of equal radius. Read today, Euclid's *Elements* (300 BCE/2002) in effect provides instructions for dynamic-geometry constructions. The "elements" of geometry are not so much the points, lines, circles, triangles and quadrilaterals, but the basic operations of constructing figures with important relationships, such as congruence or symmetry. Just as Euclidean geometry contributed significantly to the development of logical, deductive, apodictic cognition in Western thought and in the formative minds of many prospective mathematicians, so collaborative experiences with dynamic geometry may foster in students ways of thinking about dependencies in the world.

The students in the case study used Euclid's method to construct the outside triangle, but soon realized that the same procedure could not be used to construct the inscribed triangle because of the additional constraint that its vertices all had to be on the sides of the inscribing triangle, which they had constructed. Considerable further dragging of points in the given figure and experimentation with various construction approaches were tried. Finally, the students noticed that when one point of the inner triangle was dragged along a side of the outer triangle, the other vertices of the inner triangle moved in a corresponding way, such that their positions along their sides of the outer triangle were the same as that of the dragged vertex on its side. Then they quickly decided to use the method they had learned for copying a line-segment length. They copied the length from one outer vertex of their new equilateral triangle to a point for an inner vertex. Then they placed this length along the other sides, starting at both of the other vertices. This determined the locations of the other inner vertices. When they connected the three points, they formed an inscribed triangle. When any point or line was dragged, both the inner and outer triangles remained equilateral and inscribed.

In their sixth session, the students tackled the topic of inscribed squares. All their previous work in dynamic geometry had involved triangles and they had not been exposed to a method of constructing a dynamic square. They spent most of the hour exploring possible construction methods, eventually inventing a method that was elegantly similar to that of the triangle construction. All three students then immediately saw how to construct the interior square by copying the length from a corner of the exterior square to a corner of the interior one along a side. In Figure 3, the circles used for copying the length are still visible. The clarity with which each of the students understood how to inscribe a square—once they were able to construct the exterior dynamic square—shows how well they had each individually mastered the technique from their prior collaborative experience involving the dynamic triangles.

Their collaborative solution of the inscribed-triangles topic is quite typical. We have observed a number of small groups working on this topic, including math teachers, researchers, graduate students and middle-school students. They all go through a similar process of dragging the original figure, experimenting with construction attempts, discovering the dependency of the distances between the interior and exterior vertices, then realizing how to copy that distance and finally checking that their construction has the same behavior as the given figure. While this topic poses a problem that is difficult for individuals, small groups often stick with it and solve it through collaborative effort within an hour or less. It takes a combination of many trials, observations and connections to accomplish the task. The collaborative approach allows individuals to contribute specific pieces of the puzzle, to build on each other's proposals and to discuss the implications.

The chat discourse is striking in how much the students make sure that everyone agrees with and understands each step that the group as a whole takes in constructing their figures. In addition to expressing agreement and affirming understanding, the students also demonstrate their *shared understanding* by fluidly building on each other's contributions. Successive steps are generally taken by different students, indicating that they are all following the logic of the collaborative effort.

Contributing to Group Cognition

The cognition in group cognition is not the same as individual cognition; it relies upon individual cognition to make essential contributions. However, one cannot say that all of the cognition should be analyzed at the individual unit, because the work of assembling the high-level argumentative structure occurs at the group unit of analysis. Surely, putting together longer sequences of problem-solving arguments must be considered a cognitive activity as much as the work that goes into making the detailed contributions to individual steps. In addition, the personal contributions of individual utterances are largely responses to what has gone before in the group interaction. Not only are these contributions expressions that would not have occurred without the preceding opening up for them and elicitation of them by the group process, but many of the contributions are largely reactions at the group level, which reference and inter-relate resources available in the discourse context more than they introduce new elements from the personal perspective and individual background of the actor. The important cognitive achievement of solving the problem is emergent at the group level, rather than a simple collection of expressions of individual cognitive accomplishments.

Coherent and impressive examples of group cognition—such as solving a math problem that the group members would not have been able to solve on their own—do not occur whenever a number of people come together in conversation. In fact, the research field of computer-supported collaborative learning has documented that desirable forms of collaborative knowledge building are hard to find. The three studies summarized above indicate some reasons for this. First, it is difficult to set up a group interaction where everything relevant to the cognition at the group level of analysis is captured in a form adequate for detailed analysis. It took years of research to develop and deploy the VMT environment to successfully generate adequate data for the analysis of group cognition. Secondly, the group interaction must be directed and guided to focus on an appropriate cognitive task. Certain challenging math problems, carefully presented, seem to provide effective resources for stimulating interesting episodes of group cognition.

Additionally—as the three studies summarized here have documented—the groups must work consistently to ensure the presence of certain preconditions of effective group cognition. They must persist in building *longer sequences* of responses to each other, they must maintain continuous *co-attention* to a shared focus of discussion, and they must build and sustain a *shared understanding* of the topic of conversation.

The Constitution of Group Cognition

The phenomenological tradition has always conceived of cognition as embodied in the world, rather than as a Cartesian mental process. Husserl (1929/1960, §14) emphasized that cognition is cognition *of* something; it is located at its object, not at some internal representation of that external object. Heidegger (1927/1996) therefore started from the experience of being-in-the-world instead of thinking-in-the-head. For him, cognition is a matter of being-with and caring-for things and people. The world is a shared world and the things we are there with are always already understood as meaningful. In Merleau-Ponty's (1945/2002) famous example of the blind man with the cane, the cane does not so much augment or extend the man's senses and mental awareness of external reality as it locates his cognition in the physical world at the tip of the cane; he senses the object at the tip directly, without focusing on the cane or the intervening distance.

If we look at the presented examples of group cognition, we see that the students are "there" in their group interaction with virtual mathematical objects, seen in specific ways. Aznx and Bwang have drawn the horizontal sticks and the vertical sticks separately (not shown in the summary above). They have noticed a four-way symmetry, which allows them to reduce the problem of counting the sticks to a tractable pattern. They are focused together on the diamond as that symmetric pattern of sticks. Similarly, Jason, Qwertyuiop and 137 have worked hard to view their hexagonal array as a symmetrical pattern of sticks forming lines within triangles that make up a hexagon. As these groups work out their algebraic solutions to the topic, they are present together in a shared virtual world at an object of interest, which they all see as structured in the same way. In the third case, after much work individually and collaboratively, and incorporating ideas from the ancient tradition of Euclidean geometry, the three students working on the inscribed squares all observe that when square EFGH is dragged within square ABCD the following segments along the outer square change but stay equal in length to each other: AE, CH, DG, BF. They then can all see that they have to construct square MONP within square IJKL so that segments IP, JM, KO, LN stay the same (see Figure 3). They collaborate in a shared world, manipulating a shared object physically (i.e., by moving a mouse), visually and imaginatively within a shared approach to their problem, the geometric objects, the dynamic dependencies, the representational figure and the software affordances.

Following the phenomenologists, ethnomethodologists showed that the shared social world is constituted continuously through group interaction (Garfinkel, 1967). In our VMT data, we can study precisely how that is accomplished. We see that it takes place over longer sequences of discourse moves, each centered on elicitation/response adjacency pairs. Carrying out these longer sequences requires maintaining persistent co-attention to a shared object; the being-there-together at the object provides a shared focus for the discourse. Accompanying this, there must be a shared understanding of the object and of the discourse context so that group members understand each other. If someone does not know what someone else means by a “hexagonal array” or by its “side-length,” does not see the same elements of a symmetrical pattern or the same set of line segments moving together, then the collaborative problem solving cannot continue productively.

Kant (1787/1999) argued that the human mind constitutes meaningful reality through a process of creative discovery, in which structure is imposed by the mind to create and discover (constitute) objects in the world. In the preceding examples, we see how group interaction can constitute the character of objects in the shared world and we have suggested that the shared meaningful world is itself constituted through such interaction. The nature of reality—such as the symmetries of diamond patterns, hexagonal arrays and inscribed squares—is discovered through the creation of interpretive views of objects. Effective perspectives are constrained by reality, which is not knowable except through these views.

The creation of perspectives at the level of group cognition shifts the constitutive role from Kant’s individual cognition to group and social cognition. Like the students in the virtual math teams, *we first learn to see things as others see them in group-cognitive processes* (which generally incorporate culturally sanctioned approaches). Subsequently—due to the power of language (e.g., naming, verbal description)—we can be there with those objects (diamonds, hexagons, squares) when we are not physically (or virtually) present with them in a shared group setting. We can even “internalize” (to use Vygotsky’s metaphor) our ability to be-there-with these meaningful objects in the internal speech of individual thought.

However, the fact that introspection of adults discovers (and assumes) the existence of many individual mental objects does not mean that those objects were not at some point in our development internalized from group-cognitive experiences in community contexts. An adequate analysis of cognition should recognize the constitutive roles of group cognition and their integration with phenomena of individual and social cognition.

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14. Sustaining Group Cognition

Abstract. Learning takes place over long periods of time that are hard to study directly. Even the learning experience involved in solving a single challenging math problem in a collaborative online setting can be spread across hundreds of brief postings during an hour or more. Such long-term interactions are constructed out of posting-level interactions, such as the strategic proposing of a next step. This Investigation identifies a pattern of exchange of postings that it terms *math-proposal adjacency pair*, and describes its characteristics. Drawing on the methodology of conversation analysis, the Investigation adapts this approach to examining mathematical problem-solving communication and to the computer-mediated circumstances of online chat. Math proposals and other interaction methods constitute the collaborative group as a working group, give direction to its problem solving, and help to sustain its intersubjective meaning making or group cognition. Groups sustain their online social and intellectual work by building up longer sequences of math proposals, other adjacency pairs and a variety of interaction methods. Experiences of collaboration and products of group cognition emerge over time.

Keywords. Longer sequences, math-proposal adjacency pair, failed proposal, design-based research, sustaining interaction.

Sustaining Interaction in a CSCL Environment

Research in learning has traditionally focused on psychological processes at the individual unit of analysis. With the shift to socio-cultural approaches in recent years, the community unit of analysis came to the fore. In my writings on group cognition, I identified small groups as defining a middle ground between individual people and communities of practice:

> Small groups are the engines of knowledge building. The knowing that groups build up in manifold forms is what becomes internalized by their members as individual learning and externalized in their communities as certifiable knowledge. At least, that is a central premise of this book. (Stahl, 2006b, p. 16)

The concept of group cognition, however, retains a certain ambiguity of scale. On the micro level, it is based on the discovery by conversation analysis that a smallest element of interaction in discourse is the adjacency pair, a product of interaction within a dyad or small group, and not an expression of one or more individuals' cognition (Duranti, 1998; Schegloff, 1991). On the macro level, it is a vision of collaborative knowledge building, where knowledge arises through community, interpersonal or social interaction (Scardamalia & Bereiter, 1996; Vygotsky, 1930/1978; Lave & Wenger, 1991, respectively). Taking one approach or the other, we can analyze how participants in a small group of students build a detailed point of shared knowledge, how they develop their mediated cognition or how they apprentice participation in the community of math discourse. The question remains: how can we understand not just the results, but also what happens in the group at the interesting meso level of the small group itself during a one-hour math chat consisting of many detailed interactions but perhaps not measurably increasing the group's knowledge, skills or community participation?

This Investigation tries to address the gap in the methodology of the learning sciences in a preliminary way. It begins with a detailed analysis of a particular interaction that actually occurred in a student chat. It then gradually broadens the discussion of online math chat sessions, discussing various aspects of how the elemental adjacency pairs in such a momentary interaction contribute to a sustained group experience over a somewhat longer period of time. The presentation proceeds through these steps:

The setting of online math chats, which provide the experimental context for our observations, is first motivated and described.

The concept of adjacency pairs from conversation analysis is adapted to the situation of online math chats and is particularized as "math-proposal adjacency pairs."

A specific adjacency pair is analyzed as a "failed proposal," which by contrast sheds light on the nature of successful proposals.

We then describe our design-based research approach in which we revise our software and pedagogy in response to issues observed during a sequence of evolving trials.

Next, we look at a more extended interaction that occurred in our revised chat environment, involving methods of computer-supported deictic referencing that build from adjacency pairs to longer sequences of cognitive work.

- To extrapolate beyond one or two detailed interactions and analyze more extended sessions with some generality would require volumes of exposition. We therefore rely on our other studies, our general impressions from observing and participating in many online math chats, and from related work by others to discuss a number of relevant aspects of sustained group cognition.
- We conclude with reflections on how groups construct and sustain their on-going sense of shared experience. This points to future work.

Doing mathematics together online

Technology-enhanced learning offers many opportunities for innovation in education. One of the major avenues is by supporting the building of collaborative meaning and knowledge (Stahl, 2006b). For instance, it is now possible for students around the world to work together on challenging math problems. Through online discussion, they can share problem-solving experiences and gain fluency in communicating mathematically. Research on mathematics education stresses the importance of student discourse about math (NCTM, 2000; Sfard, 2002), something that many students do not have opportunities to practice face-to-face.

While much research on computer-supported collaborative learning (CSCL) has analyzed the use of asynchronous threaded discussion forums, there has been relatively little research on the use of synchronous chat environments in education. The research reported here suggests that chat has great promise as a medium for collaborative learning if the medium and its use are carefully configured. Here, we investigate how math discourse takes place within the chat medium and how we use our analyses to inform the design of effective math chat environments.

In the beginning of the Virtual Math Teams (VMT) research project at the Math Forum, we invited middle-school students to participate in online chats about interesting problems in beginning algebra and geometry. The following math problem, discussed in the chat excerpt analyzed below, is typical:

> If two equilateral triangles have edge-lengths of 9 cubits and 12 cubits, what is the edge-length of the equilateral triangle whose area is equal to the sum of the areas of the other two?

We rely on a variety of approaches from the learning sciences to guide our research and to analyze the results of our trials, including coding along multiple dimensions (Strijbos & Stahl, 2005), analysis of threading (Cakir *et al.*, 2005) and ethnography (Shumar, 2006). In particular, we have developed an ethnomethodologically informed (Garfinkel, 1967; Heritage, 1984) chat analysis approach based on conversation analysis (Pomerantz & Fehr, 1991; Psathas, 1995; Sacks, 1992; Sacks, Schegloff, & Jefferson, 1974; ten Have, 1999) to understand the structure of interactions that take place in student chats. In this paper, we adapt a finding of conversation analysis to math chats and analyze a specific form of adjacency pairs that seem to be important for this context. Before presenting these findings, it may be useful to describe briefly how the notion of adjacency pairs differs from naïve conceptions of conversation.

There is a widespread commonsense or folk-theory (Bereiter, 2002; Dennett, 1991) view of conversation as the exchange or transmission of propositions. This view was refined and formalized by logicians and cognitive scientists as involving verbal “expression” in meaningful statements by individuals, based on their internal mental representations (Shannon & Weaver, 1949). Speech served to transfer meanings from the mind of a speaker to the mind of a listener, who then interpreted the expressed message. Following Wittgenstein (1953) in critiquing this view, speech act theory (Austin, 1952; Searle, 1969) argued that the utterances spoken by individuals were ways of acting in the world, and were meaningful in terms of what they accomplished through their use and effects. Of course, the expression, transmission and interpretation of meaning by individuals can be problematic, and people frequently have to do some interactional work in order to re-establish a shared understanding. The construction of common ground has been seen as the attempt to coordinate agreement between individual understandings (Clark & Brennan, 1991).

Conversation analysis takes a different view of conversation. It looks at how interactional mechanisms, like the use of adjacency pairs, co-construct inter-subjectivity.

> *Adjacency pairs* are common sequences of utterances by different people—such as mutual greetings or question/answer interchanges—that form a meaningful speech act spanning multiple utterances, which cannot be attributed to an individual or to the expression of already formed mental states. They achieve meaning in their very interaction.

We are interested in what kinds of adjacency pairs are typical for math chats. The topic of adjacency pairs is taken up extensively in two sections below. Stahl (2006b) further discusses the implications that viewing adjacency pairs as the smallest elements of interactional meaning making has for the intersubjective foundation of group cognition, a process of jointly constructing meaning in discourse.

The medium of online chat has its own peculiarities (Lonchamp, 2006; Mühlpfordt & Wessner, 2005; O'Neill & Martin, 2003). Most importantly, it is a text-based medium, where interaction takes place by the sequential response of brief texts to each other (Livingston, 1995; Zemel, 2005). As a quasi-synchronous medium (Garcia & Jacobs, 1999), chat causes confusion because several people can be typing at once and their texts can appear in an order that obscures to whom or to what they are responding. Furthermore, under time pressure to submit their texts so that they will appear near the post to which they are responding, some chat participants break their messages into several short texts. Because of these peculiarities of chat, it is necessary for researchers to carefully reconstruct the implicit threading of texts that respond to each other before attempting to interpret the flow of interaction (Cakir *et al.*, 2005; Strijbos & Stahl, 2005).

Math chats differ from ordinary informal conversation in a number of additional ways. They are focused on the task of solving a specific problem, and they take place within a somewhat formal institutional setting. They involve the *doing* of mathematics (Livingston, 1986). And, of course, they are computer-mediated rather than face-to-face. The approach of conversation analysis is based on ethnomethodology (Garfinkel, 1967), which involves the study of the *methods* that people use to accomplish what they are doing. So, we are interested in working out the methods that are used by students in online math chats. In this paper, we discuss a particular method of collaboration in math chats that we have elsewhere called *exploratory participation*: participants engage each other in the conjoint discovery and production of both the problem and possible solutions (Wegerif, 2006; Zemel, Xhafa, & Stahl, 2005).

Math-proposal adjacency pairs

In order to begin to analyze the methods that students use in math chats, we take a close look at an excerpt from an actual chat. Log 1 shows an excerpt from near the beginning of the log of one of our first online collaborative math problem-solving sessions. Three students—named Avr, Sup and Pin—have just entered the chat room, said hello to each other and read the problem involving three triangles.

1. Avr (8:21:46 PM): Okay, I think we should start with the formula for the area of a triangle
2. Sup (8:22:17 PM): ok
3. Avr (8:22:28 PM): A = 1/2bh
4. Avr (8:22:31 PM): I believe
5. pin (8:22:35 PM): yes
6. pin (8:22:37 PM): i concue
7. pin (8:22:39 PM): concur*
8. Avr (8:22:42 PM): then find the area of each triangle
9. Avr (8:22:54 PM): oh, wait
10. Sup (8:23:03 PM): the base and heigth are 9 and 12 right?
11. Avr (8:23:11 PM): no
12. Sup (8:23:16 PM): o
13. Avr (8:23:16 PM): that's two separate triangles
14. Sup (8:23:19 PM): ooo
15. Sup (8:23:20 PM): ok
16. Avr (8:23:21 PM): right
17. Avr (8:23:27 PM): i think we have to figure out the height by ourselves
18. Avr (8:23:29 PM): if possible
19. pin (8:24:05 PM): i know how
20. pin (8:24:09 PM): draw the altitude'
21. Avr (8:24:09 PM): how?
22. Avr (8:24:15 PM): right
23. Sup (8:24:19 PM): proportions?
24. Avr (8:24:19 PM): this is frustrating
25. Avr (8:24:22 PM): I don't have enough paper

26. pin (8:24:43 PM): i think i got it
27. pin (8:24:54 PM): its a 30/60/90 triangle
28. Avr (8:25:06 PM): I see
29. pin (8:25:12 PM): so whats the formula

Log 1. Excerpt of 3½ minutes from a one-hour chat log. Three students chat about a geometry problem. Line numbers have been added and screennames anonymized; otherwise, the transcript is identical to what the participants saw on their screens.

The first thing to notice here is a pattern of proposals, discussions and acceptances similar to what takes place in face-to-face discourse. Bids for proposals about steps in solving the math problem are made by Avr in lines 1, 3, 8, 17 and by Pin in lines 20, 27. These proposals are each affirmed by someone else in lines 2, 6, 10, 19, 22, 28, respectively.

To avoid chat confusion, note that line 21 responds to line 19, while line 22 responds to line 20. The timestamps show that lines 20 and 21 effectively overlapped each other chronologically: Avr was typing line 21 before he/she saw line 20. Similarly, lines 24 and the following were responses to line 20, not line 23. We will correct for these confusions later, in Log 2, which reproduces a key passage in this excerpt.

In Log 1, we see several examples of a three-step pattern:

A proposal bid is made by an individual for the group to work on: "I think we should…."

A proposal acceptance is made on behalf of the group: "Ok," "right."

There is an elaboration of the proposal by members of the group. The proposed work is begun, often with a secondary proposal for the first sub-step.

The three-step pattern consists of a pair of postings—a bid and an acceptance—that form a proposal about math, and some follow-up effort. This suggests that collaborative problem solving of mathematics may often involve a particular form of adjacency pair. We will call this a *math-proposal adjacency pair*.

Here are six successful math-proposal adjacency pairs from Log 1:

1. Avr: Okay, I think we should start with the formula for the area of a triangle
2. Sup: ok

3. Avr: A = 1/2bh
6. pin: i concue

8. Avr: then find the area of each triangle
10. Sup: the base and heigth are 9 and 12 right?

17. Avr: i think we have to figure out the height by ourselves
19. pin: i know how

20. pin: draw the altitude'
22. Avr: right

27. pin: its a 30/60/90 triangle
28. Avr: I see

Note from the line numbers that the response is not always literally immediately adjacent to the bid in the chat log due to the complexities of chat posting. But the response is logically adjacent as an up-take of the bid.

Many varieties of adjacency pairs allow for the insertion of other pairs between the two parts of the original pair, delaying completion of the original pair. For instance, a question/answer pair may be delayed by utterances seeking clarification of the question. As we will see below, the clarification interaction may itself consist of question/answer pairs, possibly with their own clarifications—this may continue recursively. With math-proposal adjacency pairs, the subsidiary pairs seem to come after the completion of the original pair, in the form of secondary proposals, questions or explanations that start to do the work that was proposed in the original pair. This characteristic leads to their role in sustaining group inquiry.

Math proposals tend to lead to some kind of further mathematical work as a response to carrying out what the proposal. Often—as seen in the current example—that work consists of making further proposals. In this way, the three-step structure of the math-proposal adjacency pair starts to sustain the group interaction. The proposal bid by one person calls forth a proposal response by someone else. If the response is one of acceptance, it in turn calls forth some further work to be done or a bid for another proposal. If the response is a rejection, it may lead to justification, discussion and negotiation. Since the "preferred" response to a proposal is a statement of acceptance, a response of rejection tends to require some further work.

It is striking that the work proposed by a proposal is not begun until there is agreement with the proposal bid. This may represent consent by the group as a whole to pursue the proposed line of work. Of course, this idea is not so clear in the current example, where there are only three participants, and the interaction often seems to take place primarily between pairs of participants. As confirmed by other chat examples, however, the proposal generally seems to be addressed to the whole group and opens the floor for other participants to respond. The use of "we" in "we should" or "we have to" (stated or implied) constitutes the multiple participants as a plural subject—an effective unified group (Lerner, 1993)[8]. Anyone other than the proposer may respond on behalf of the group. The fact that the multiple participants are posited as a group for certain purposes, like responding to a proposal bid, by no means rules out their individual participation in the group interaction from their personal perspectives, or even their independent follow-up work on the math. It simply means that the individual who responds to the bid may be doing so on behalf of the group.

Moreover, there seems to be what in conversation analysis is called an interactional *preference* (Schegloff, Jefferson, & Sacks, 1977) for acceptance of the proposal. That is, if one accepts a proposal, it suffices to briefly indicate agreement: "ok." If one wants to reject a proposal, however, then one has to account for this response by giving reasons. If the group accepts the bid, one person's response may serve on behalf of the group; if the group rejects the bid, several people may have to get involved.

We would like to characterize in more detail the method of making math-proposal adjacency pairs. Often, the nature of an interactional method is seen most clearly when it is breached (Garfinkel, 1967). Methods are generally taken-for-granted by people; they are not made visible or conducted consciously. It is only when there is a *breakdown* (Heidegger, 1927/1996; Winograd & Flores, 1986) in the smooth, tacit performance of a method that people focus on its characteristics in order to overcome the breakdown. The normally transparent method becomes visible in its breach. In common-sense terms we say, "The exception proves the rule," meaning that when we see why something is an exceptional case it makes clear the rule to which it is an exception. Heidegger made this into an ontological principle, whereby things first become experience-able during a breakdown of understanding. Garfinkel uses this, in turn, as a methodological fulcrum to make visible that which is commonly assumed and is effective but unseen.

We can interpret Sup's posting in line 23 as a *failed proposal*. Given the mathematics of the triangle problem, a proposal bid related to proportionality, like Sup's, might have been fruitful. However, in this chat, line 23 was effectively ignored by the group. While its character as a failed proposal did not become visible to the participants, it can become clear to us by comparing it to successful proposal bids in the same chat and by reflecting on its sequential position in the chat in order to ask why it was not a successful bid. This will show us by contrast what the characteristics are that make other proposal bids successful.

[8] The fact that the students use "we" indicates that they are taking the set of participants to be a functional group. From an ethnomethodological perspective, this justifies the analysis of the chat as a group product since the participants themselves adopt this stance.

A failed proposal

Let us look at line 23 in its immediate interactional context in Log 2. We can distinguish a number of ways in which it differed from successful math proposal bids that solicited responses and formed math-proposal adjacency pairs:

17, 18. Avr (8:23:29 PM): i think we have to figure out the height by ourselves … if possible
19. pin (8:24:05 PM): i know how
21. Avr (8:24:09 PM): how?
20. pin (8:24:09 PM): draw the altitude'
22. Avr (8:24:15 PM): right
24. Avr (8:24:19 PM): this is frustrating
23. Sup (8:24:19 PM): proportions?

Log 2. Part of the chat log excerpt in Log 1, with order revised based on threading of the postings.

(a) All the other proposal bids (1, 3, 8, 17, 20, 27) were stated in relatively complete sentences. Additionally, some of them were introduced with a phrase to indicate that they were the speaker's proposal bid (1. "I think we should …"; 17. "I think we have to …"; 20. "i know how …"; and 27. "i think i got it …"). The exceptions to these were simply continuations of previous proposals: line 3 provided the formula proposed in line 1 and line 8 proposed to "then" use that formula. Line 23, by contrast, provided a single word with a question mark. There was no syntactic context (other than the question mark) within the line for interpreting that word and there was no reference to semantic context outside of the line. Line 23 did not respond in any clear way to a previous line and did not provide any alternative reference to a context in the original problem statement or elsewhere. For instance, Sup could have said, "I think we should compute the proportion of the height to the base of those equilateral triangles."

(b) The timing of line 23 was particularly unfortunate. It exactly overlapped a line from Avr. Because Avr had been setting the pace for group problem solving during this part of the chat, the fact that she was involved in following a different line of inquiry spelled doom for any alternative proposal around the time of line 23. Pin either seemed to be continuing on his own thread without acknowledging anyone else at this point, or else he was responding too late to previous postings. So, a part of the problem for Sup was that there was little sense of a coherent group process—and what sense there was did not include him. If he was acting as part of the group process, for instance posing a question in reaction to Pin and in parallel to Avr, he was not doing a good job of it and so his contribution was ignored in the group process. It is true that a possible advantage of text-based interaction like chat over face-to-face interaction is that there may be a broader time window for responding to previous contributions. In face-to-face conversation, turn-taking rules may define appropriate turns for response that expire in a fraction of a second as the conversation moves on. In computer-based chat, the turn-taking sequence is more open. However, even here if one is responding to a posting that is several lines away, it is important to make explicit somehow the post to which one is responding. Sup could have said, "I know another way to find the height: using proportions." His posting does not do anything like that; it relies purely upon sequential timing to establish its context, and that fails in this case.

(c) Sup's posting 23 came right after Pin's proposal bid 20: "draw the altitude." Avr had responded to this with 22 ("right"), but Sup seems to have ignored that. Pin's proposal had opened up work to be done, and both Avr and Pin responded after line 23 with contributions to this work. So, Sup's proposal bid came in the middle of an ongoing line of work without relating to it. In sequential terms, he made a bid for a proposal when it was not time to make a proposal. Sup's proposal bid was not positioned within the group effort to sustain a promising line of inquiry. It is like trying to take a conversational turn when there is not a pause that creates a turn-taking opportunity. Now, it is possible—especially in chat—to introduce a new proposal at any time. However, to do so effectively, one must make a special effort to bring the on-going work to a temporary halt and to present one's new proposal as an alternative. Simply saying "proportions?" will not do it. Sup could have said, for instance, "Instead of drawing the altitude, let's use proportions to find it."

(d) To get a proposal response to a proposal bid, one can elicit at least an affirmation or recognition. Again, this is a matter of pre-structuring a sustained interaction. Line 23 does not really solicit a response. For instance, Avr's question, 21: "how?" called for an answer—that was given by Pin in line 20, which actually appeared in the chat window just prior to the question and with the same time stamp. But Sup's posting does not call for a specific kind of answer. Even Sup's own previous proposal bid in line 10 ended with "right?"—requesting agreement or disagreement. Line 10 elicited a clear response from Avr, line 11 ("no") followed by an exchange explaining why Sup's proposal was not right.

(e) Other proposal bids in the excerpt are successful in contributing to sustaining the collaborative knowledge building or group problem solving in that they open up a realm of work to be done. One can look at Avr's successive proposal bids on lines 1, 3, 8 and 17 as laying out a work strategy. This elicits a proposal response from Sup trying to find values to substitute into the formula and from Pin trying to draw a graphical construction that will provide the values for the formula. Sup's proposal bid in line 23, however, neither calls for a response nor opens up a line of work. There is no request for a reaction from the rest of the group, and the proposal bid is simply ignored. Since no one responded to Sup, he could have continued by doing some work on the proposal himself. He could have come back and made the proposal more explicit, reformulated it more strongly, taken a first step in working on it, or posed a specific question related to it. But he did not—at least not until much later—and the matter was lost.

(f) Another serious hurdle for Sup was his status in the group at this time. In lines 10 through 16, Sup had made a contribution that was taken as an indication that he did not have a strong grasp of the math problem. He offered the lengths of the two given triangles as the base and height of a single triangle (line 10). Avr immediately and flatly stated that he was wrong (line 11) and then proceeded to explain why he was wrong (line 13). When he agreed (line 15), Avr summarily dismissed him (line 16) and went on to make a new proposal that implied his approach was simply wrong (lines 17 and 18). Then Pin, who had stayed out of the interchange, re-entered, claiming to know how to implement Avr's alternative proposal (lines19 and 20) and Avr confirmed that (line 22). Sup's legitimacy as a source of useful proposals had been totally destroyed at precisely the point just before he made his ineffective proposal bid. Less than two minutes later, Sup tries again to make a contribution, but realizes himself that what he says is wrong. His faulty contributions confirm repeatedly that he is a drag on the group effort. He makes several more unhelpful comments later and then drops out of the discourse for most of the remaining chat. Sustaining a math chat discourse involves work to maintain an ongoing social interaction as well as work to continue the math inquiry. Proposal bids and other postings are constrained along multiple dimensions of efforts to sustain the activity.

The weaknesses of line 23 as a proposal bid suggest (by contrast, exception, breach or breakdown) some characteristics for successful proposals:

A clear semantic and syntactic structure,

Careful timing within the sequence of postings,

A firm interruption of any other flow of discussion,

The elicitation of a response,

The specification of work to be done and

A history of helpful contributions.

In addition, there are other interaction characteristics and mathematical requirements. For instance, the level of mathematical background knowledge assumed in a proposal must be compatible with the expertise of the participants, and the computational methods must correspond with their training. Additional characteristics become visible in other examples of chats. Successful proposals contribute in multiple ways to sustaining the group cognitive process.

As we have just seen, the formulation of effective bids for math proposals involves carefully situating one's posting within the larger flow of the chat. This is highly analogous to taking a turn in face-to-face conversation (Sacks *et al.*, 1974). Where conversation analysis developed a systematics of turn taking, we are discovering the systematics of chat interaction. This describes how math proposals and other chat methods must be designed to fit into—and thereby contribute to—the sustained flow of group interaction.

So far in this Investigation, the notion of math-proposal adjacency pairs has been illustrated in just a single chat log excerpt. But in our research, we have seen both successful and failed math proposals many times. Other researchers have also noted the role of successful and failed proposals in collaborative problem solving (Barron, 2003; Cobb, 1995; Dillenbourg & Traum, 2006; Sfard & McClain, 2003).

Each proposal bid and uptake is unique—in its wording and its context. The interactional work that it does and the structuring that it employs are situated in the local details of its sequential timing and its subtle referencing of unique and irreproducible elements of the on-going chat. Each group of students develops somewhat different methods of engaging with math problems and making math proposals. Even within a given chat, each posting pair that might be a proposal must be analyzed as a unique, meaning-making interaction in order to determine if it is in fact a math-proposal adjacency pair. That is why case studies provide the necessary evidence. The essential details of interaction methods are lost in aggregation, in the attempt to overcome what Garfinkel (1967) terms the "irreducible indexicality" of the event. To the extent that identifying proposal pairs is a useful analytic approach, it is important to determine what interactional methods of producing such proposals are effective (or not) in fostering successful knowledge building and group cognition, as we have begun to do here.

An understanding of methods like proposal making can guide the design of activity structures for collaborative math. As we are collecting and analyzing a corpus of chat logs under different technological conditions, we are evolving the design of computer support through iterative trials and analyses.

Designing computer support

If the failure of Sup's proposal about proportions is considered deleterious to the collaborative knowledge building around the triangles problem, then what are the implications of this for the design of educational computer-based environments? One response would be to help students like Sup formulate stronger proposals. Presumably, giving him positive experiences of interacting with students like Avr and Pin, who are more skilled in chat proposal making, would provide Sup with models and examples from which he can learn—assuming that he perseveres and does not drop out of the chat.

Another approach to the problem would be to build functionality into the software and structures into the activity that scaffold the ability of weak proposal bids to survive. As students like Sup experience success with their proposals, they may become more aware of what it takes to make a strong proposal bid.

Professional mathematicians rely heavily upon inscription—the use of specialized notation, the inclusion of explicit statements of all deductive steps and the format of the formal proof to support the discussion of math proposals—whether posted on an informal whiteboard, scrawled across a university blackboard or published in an academic journal. Everything that is to be referenced in the discussion is labeled unambiguously. To avoid ellipsis, theorems are stated explicitly, with all conditions and dependencies named. The projection of what is to be proven is encapsulated in the form of the proof, which—at least since Euclid—starts with the givens and concludes with what is proven. Perhaps most importantly, proposals for how to proceed are listed in the proof itself as theorems, lemmas, etc. and are organized sequentially. (This view of proof is an idealization that abstracts from unstated tacit background knowledge of the mathematical community, as Livingston (1999) and Wittgenstein (1944/1956) before him have demonstrated.)

One could imagine a chat system supplemented with a window containing an informal list of proposals analogous to the steps of a proof. After Sup's proposal, the list might look like Figure 1. When Sup made a proposal in the chat, he would enter a statement of it in the proof window in logical sequence. He could cross out his own proposal when he felt it had been convincingly argued against by the group (see dashed lines in Figure 1 crossing out the proposal that base and height = 9 and 12).

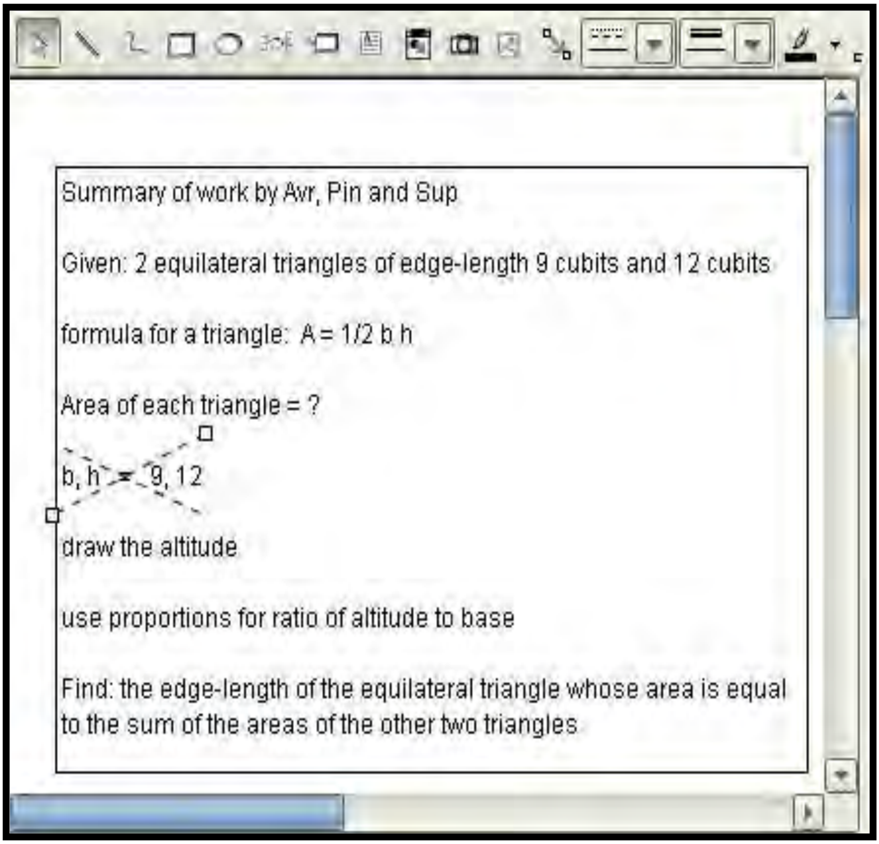

Figure 1. A software interface window with a list of proposals.

The idea is that important proposals that were made would be retained in a visible way and be shared by the group. Of course, there are many design questions and options for doing something like this. Above all, would students understand this functionality and how would they use it? The design sketch indicated in Figure 1 is only meant to be suggestive.

Another useful tool for group mathematics would be a shared drawing area. In the chat environment used by Sup, Pin and Avr, there was no shared drawing, but a student could create a drawing and email it to the others. Pin did this twelve minutes after the part of the interaction shown in the excerpt. Before the drawing was shared, much time was lost due to confusion about references to triangles and vertices. For math problems involving geometric figures, it is clearly important to be able to share drawings easily and quickly. Again, there are many design issues, such as how to keep track of who drew what, who is allowed to erase, how to point to items in the drawing and how to capture a record of the graphical interactions in coordination with the text chatting.

Because we are designing a computer-supported experience that has never before existed and because we want our design to be based on detailed study of how students actually create their collaborative experience in the environment we are designing, we follow a highly iterative try-analyze-redesign cycle of design-based research (Design-Based Research Collective, 2003), in order to gradually approach an effective computer-supported environment and math discourse community.

We started with a simple online service. We used AOL's IM commercial chat system that was already familiar to many students. We invited students into chat rooms and presented a problem from the Math Forum's well-established Problem of the Month service. An adult facilitator was present in the room to help with any technical problems. When we saw how necessary a shared whiteboard was, we tried an open-source solution and also WebCT's and Blackboard's interactive classrooms. Eventually we collaborated with researchers in Germany to use and further develop ConcertChat. Together, we have gradually evolved ConcertChat into a sophisticated environment for students, instrumented to capture student interaction for researchers.

Since the early AOL-based chat analyzed above, we have gone through many cycles of design, trial and analysis. In addition to designing wiki support for persistent summaries of work (such as that in Figure 3) and a shared whiteboard for constructing geometric drawings (discussed in the following section), we have incorporated the following: a referencing tool; a way for users to explicitly thread their chat postings; several forms of social awareness; tutorials on how to use the new features; a help system on using the tools, collaborating and problem-solving; and a lobby to support group formation. We have also experimented extensively with how best to formulate math problems or topics and how to provide feedback to students on their work.

References and threading

The more we study chat logs, the more we see how interwoven the postings are with each other and with the holistic Gestalt of the interactional context that they form. There are many ways in which a posting can reference elements of its context. The importance of indexicality to creating shared meaning was stressed by Garfinkel (1967). Vygotsky also noted the central role of pointing for mediating intersubjectivity in his analysis of the genesis of the infant-and-mother's pointing gesture (1930/1978, p. 56). Our analysis of face-to-face collaboration emphasized that spoken utterances in collaborative settings tend to be elliptical, indexical and projective ways of referencing previous utterances, the conversational context and anticipated responses (Stahl, 2006b, chapter 12).

Based on these practical and theoretical considerations—and working with the ConcertChat developers—we evolved the VMT-Chat environment. As shown in Figure 2, it not only includes a shared whiteboard, but has functionality for referencing areas of the whiteboard from chat postings and for referencing previous postings [Investigation 22]. The shared whiteboard is necessary for supporting most geometry problems. (This will save Avr the frustration of running out of paper, and also let Pin and Sup see what she is drawing and add to it or reference it.) Sharing drawings is not enough; students must be able to reference specific objects or areas in the drawing. (For example, Sup could have pointed to elements of the triangles that he felt to be significantly proportional.) The whiteboard also provides opportunities to post text where it will not scroll away. (Sup could have put his failed proposal in a text box in the whiteboard, where he or the others could come back to it later.) The graphical references (see the bold line from a selected posting to an area of the drawing in Figure 2) can also be used to reference one or more previous postings from a new posting in order to make the threads of responses clearer in the midst of "chat confusion" (Fuks, Pimentel, & de Lucena, 2006).

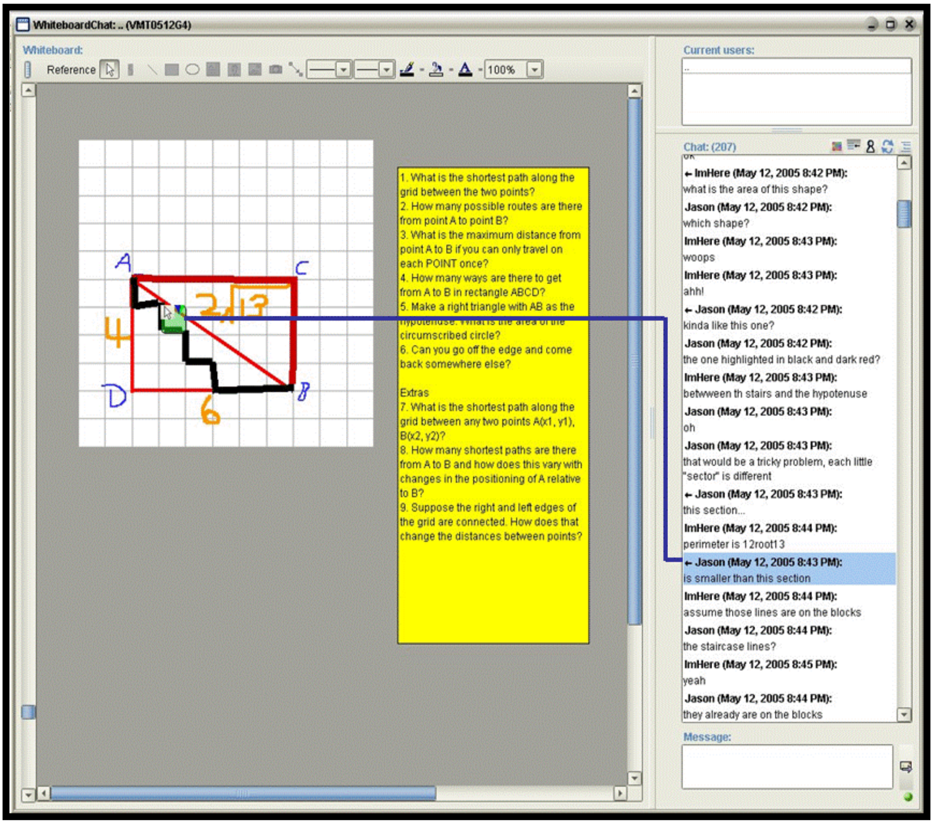

Figure 2. Screen view of VMT-Chat with referencing. Line 12 of the chat is selected.

In one of our first chats using VMT-Chat, the students engaged in a particularly complex interaction of referencing a figure in the whiteboard whose mathematics they wanted to explore [Investigation 22]. The chat log from Figure 2 (graphical references to the whiteboard are indicated by "[REF TO WB]" in the log) is listed in Log 3.

1	ImH:	what is the area of this shape? [REF TO WB]
2	Jas:	which shape?
3	ImH:	woops
4	ImH:	ahh!
5	Jas:	kinda like this one? [REF TO WB]
6	Jas:	the one highlighted in black and dark red?
7	ImH:	between th stairs and the hypotenuse
8	Jas:	oh
9	Jas:	that would be a tricky problem, each little "sector" is different
10	Jas:	this section [REF TO WB]

11	ImH:	perimeter is 12root3
12	Jas:	is smaller than this section [REF TO WB]
13	ImH:	assume those lines are on the blocks
14	Jas:	the staircase lines?
15	ImH:	yeah
16	Jas:	they already are on the blocks

Log 3. Chat log from Figure 2.

Line 1 of the chat in Log 3 textually references an abstract characteristic of a complex graphical form in the whiteboard: "the area of this shape." The software function to support this reference failed, presumably because the student, ImH, was not experienced in using it and did not cause the graphical reference line to point to anything in the drawing. Line 5 provides a demo of how to use the referencing tool. Using the tool's line, a definite textual reference ("this one") and the use of line color and thickness in the drawing, lines 5 and 6 propose an area to act as the topic of the chat. Line 7 makes explicit in text the definition of a sub-area of the proposed area. Line 8 accepts the new definition and line 9 starts to work on the problem concerning this area. Line 9 references the problem as "that" and notes that it is tricky because the area defined does not consist of standard forms whose area would be easy to compute and add up. It refers to the non-uniform sub-areas as little "sectors." Line 10 then uses the referencing tool to highlight (roughly) one of these little sectors or "sections." Line 12 continues line 10, but is interrupted in the chat log by line 11, a failed proposal bid by ImH. The chat excerpt continues to reference particular line segments using deictic pronouns and articles as well as a growing vocabulary of mathematical objects of concern: sectors, sections, lines, blocks.

Progress is made slowly in the collaborative exploration of mathematical relationships, but having a shared drawing helps considerably. The students use multiple textual and graphical means to reach a shared understanding of mathematical objects that they find interesting but hard to define. In this excerpt, we start to get a sense of the complex ways in which brief textual postings weave dense webs of relationships among each other and with other elements of the collaborative context.

This example shows how creating shared meaning can require more than a simple adjacency pair. In order to establish a reference to "this shape" that could allow the two participants to discuss that math object, the dyad had to construct a complex involving nested question/answer pairs, math proposal pairs, a failed proposal bid, drawing, coloring, labeling, pointing, multiple repairs, computations. Here we see a more sustained group-cognitive process. Across 16 postings and considerable coordinated whiteboard activity during two minutes, the student dyad defines a math object for investigation. The definition is articulated by this whole sequence of combined and intricately coordinated textual and graphical work.

Sustaining the group interaction

The goal of our research is to provide a service to students that will allow them to have a rewarding experience collaborating with their peers in online discussions of mathematics. We can never know exactly what kind of subjective experience they had, let alone predict how they will experience life under conditions that we design for them. For instance, it is methodologically illegitimate to ask if ImH already "intended" or "had in mind" in line 1 the shape that the group subsequently arrived at. We know from the log that ImH articulated much of the explicit description, but he only did this in response to Jas. If we interviewed ImH afterwards he might quite innocently and naturally project this explicit understanding back on his earlier state of mind as a retrospective account or rationalization (Suchman, 1987).

Our primary access to information related to the group experiences comes from chat logs (including the whiteboard history). The logs capture most of what student members see of their group on their computer screens. They therefore constitute a fairly complete record of everything that the participants themselves had available to understand their group interaction. We can even replay the logs so that we see how the session unfolded sequentially in time. Of course, we are not engaged in the interaction the way the participants were, and recorded experiences never quite live up to the live version because the engagement is missing. To gain some first-hand experience, we researchers do test out the environments ourselves and enjoy the experience, but we experience math and collaboration differently than do middle-school students. We also interview students and their teachers, but teenagers rarely reveal much of their life to adults.

So, we try to understand how collaborative experiences are structured as interpersonal interactions that are sustained over time. The focus is not on the individuals as subjective minds, but on the human, social group as constituted by the interactions that take place within the group. Although we generally try to ground our understanding of interaction through close, detailed analysis of excerpts from chat recordings, we do not have room to document our analysis of longer-scale structures at that level of detail here. During Spring Fest 2005, we collected over 50 hours of small-group chat about math. We engage in weekly collaborative data sessions (Jordan & Henderson, 1995) to develop case studies of unique chat excerpts. A number of published papers arising from these sessions are available. The discussion in the remainder of this Investigation is a high-level summary based on what we have observed.

Replies, up-take, pairs and triplets

Figure 3 provides a diagram of the responses of postings in the chat discussed above involving Avr, Pin and Sup (Log 1). The numbers of the posts by each participant are placed in chronological order in a column for that participant. Math-proposal adjacency pairs are connected with solid arrows and other kinds of responses are indicated with dashed arrows. Note that Sup's failed proposal bid (line 23) is isolated. Most of the chat, however, has coherence, flow or motion because most postings are responses to previous messages. This high level of responses is due to the fact that many postings elicit responses or up-take, the way that a greeting invariably calls forth another greeting in response, or a question typically elicits an answer. In a healthy conversation, most contributions by one participant are taken up by others. Conversationalists work hard to fit their offerings into the timing and evolving focus of the on-going interaction. In chat, the timing, rules and practices are different, but the importance of up-take remains [Investigation 4].

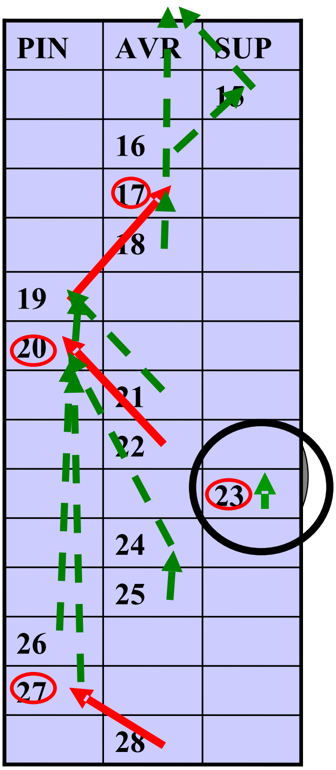

Figure 3. Threading of adjacency pairs and other uptake.

The fact that the group process and the cross ties between people are central to collaborative experiences does not contradict the continuing importance of the individuals. The representation of Figure 3 uses columns to indicate the connections and implicit continuity within the sequence of contributions made by an individual (compare the representation in Sfard & McClain, 2003). We may project psychological characteristics onto the unity of an individual's postings, attributing this unity to personal interests, personality, style, role, etc. Such attributions may change as the chat unfolds. The point is that the individual coherence and unfolding of each participant's contributions adds an important dimension of implicit sustaining connections among the postings.

Adjacency pairs like math proposals, greetings and questionings provide important ties that cut across the connections of individual continuities. They form the smallest elements of interaction precisely by binding together postings from different people. A proposal bid that is not taken up is not a meaningful proposal, but at best a failed attempt at a proposal. A one-sided greeting that is not recognized by the other is not an effective greeting. An interrogative expression that does not call for a response is no real questioning of another. These adjacency pairs are all interactional moves whose meaning consists in a give-and-take between two or more people. When we hear something that we recognize as a proposal bid, a greeting or a question, we feel required to attempt an appropriate response. We may ignore the proposal bid, snub the greeter or refuse to answer the question, but then our silence is taken as a response of ignoring, snubbing or refusing—and not simply a lack of response. The first part of an adjacency pair opens up a space of possibility for other group members to respond. The space if structured to allow certain kinds of utterances and not others. Some of the permitted responses are preferred and others are dis-preferred, requiring additional elaboration.

The way that a response is taken is an integral part of the interaction itself. In discussing the building of common ground, Clark argues that shared understanding by A and B of A's utterance involves not only B believing that he understands A, but also A agreeing that B understands (Clark & Brennan, 1991). This may require an interaction spanning multiple utterances. For instance, the most prevalent interaction in classroom discourse is when a teacher poses a question, a student provides an answer demonstrating understanding and then the teacher acknowledges the student response as such an understanding (Lemke, 1990). Here, the elemental cell of interactional meaning making is a sequence of contributions by different people.

It is clear in this analysis that the meaning is constructed through the interaction of multiple people, and is not a simple expression of pre-existing mental representations in any one individual's head. This is the philosophical importance of the concept of adjacency pair: that meaning in groups is made through the interaction of multiple people, not completely by an individual's mental activity. In calling this "group cognition," we extend the term "cognition" from individual psychology to apply to processes in which small groups through their discourse construct meaning structures like logical arguments or mathematical proofs—that is, they engage in processes which are considered thinking when conducted by individual people. This approach is consistent with dialogical theories that actually view higher-level thinking by individuals as derivative of such intersubjective meaning making (Bakhtin, 1986;

Linell, 2001; Stahl, Koschmann, & Suthers, 2006; Vygotsky, 1930/1978; Wegerif, 2006).

Longer sequences

Although much attention has been given to adjacency pairs in conversation analysis and although such pairs can be thought of as the elements of meaning making in collaborative interaction, they form only one of many levels of analysis. For instance, there are *longer sequences* (Sacks, 1992, vol. II, p. 354), *episodes* (Linell, 2001) and *topics* in dialogs and chats (Zemel, Xhafa, & Cakir, 2005) that provide layers of structure and sense. An hour-long chat is not a homogeneous interchange. A typical math chat might start with a period of introductions, greetings, socializing. Then there could be some problem-solving work. This might be periodically interrupted by joking, playing around, or silliness. People may come and go, requiring catching up and group reorganization, or even bridging across sessions. Each of these episodes has boundaries during which the group members must negotiate whether or not to stop what they were doing and start something else. These transitions may themselves be longer sequences of interaction, especially in large groups. We have barely begun to explore these different layers.

In social conversation, people work hard to strike up conversations, to propose new topics of mutual interest and to keep the conversation going. Online math chats face similar challenges. Students hesitantly greet each other and get things started. Math proposals are often used to introduce new topics and to carry forward a train of thought together. Finally, participants engage in considerable interaction work to sustain their sessions, intertwining humor, flirting, socializing and math inquiry—often using one of these modes to sustain others. Eventually every group decides to disband, at least until a future session.

The above referencing excerpt from a VMT-Chat was from the second hour-long session in a series of four chats by the same group. The sessions referred back to previous sessions and prepared for future ones. We hope to foster a community of Math Forum users who come back repeatedly to math chats, potentially with their friends. Their chats will reference other chats and different online experiences, building connections at the community level. This adds more layers of interconnections. It may sustain group interaction, inquiry and reflection over more significant periods of time.

Constructing proofs

Learning math involves becoming skillful in the social practices of the math community (Livingston, 1999). The math community is an aspect of the world-historical global community. The most central participants are the great mathematicians, who have invented new mathematical objects and developed new forms of mathematical practice (Sfard & Linchevski, 1994). Most of the population has low math literacy and participates on the periphery of the math discourse community. They are unable to manipulate math concepts fluidly in words or mathematical symbolism (Sfard, 2002). Nevertheless, they can use basic arithmetic methods for practical purposes (Lave, 1988). One of the most fundamental methods of math is counting, which young children are drilled at extensively. Formal math assumes that the practitioner is skilled at following rules, such as the non-formalized rules of numeric sequencing or counting (Wittgenstein, 1944/1956).

In our chats, students work on math problems and themes. In solving problems and exploring math worlds or phenomena, the groups construct sequences of mathematical reasoning that are related to proving. Proofs in mathematics have an interesting and subtle structure. To understand this structure, one must distinguish:

- The problem statement-and-situation;
- The exploratory search for a solution;
- The effort to reduce a haphazard solution path to an elegant, formalized proof;
- The statement of the proof; and
- The lived experience of following the proof (Livingston, 1986, 1987).

Each of these has its own structures and practices. Each implicitly references the others. To engage in mathematics is to become ensnarled in the intricate connections among them. To the extent that these aspects of doing math have been distinguished and theorized, it has been done as though there is simply an individual mathematician at work. There has been virtually no research into how these could be accomplished and experienced collaboratively—despite the fact that talking about math has for some time been seen as a priority in math education (NCTM, 1989; Sfard, 2002).

The stream of group consciousness

Psychologists like William James and novelists like Jack Kerouac have described narratives that we tell ourselves silently about what we are doing or observing as our stream of consciousness. This "inner voice" rattles on even as we sleep, making connections that Sigmund Freud found significant (if somewhat shocking in his day). In what sense might online chats—with their meanderings, flaming, associative referencing, unpredictable meaning making and unexpected images—deserve equal status as streams of (group) consciousness? Group cognition can be self-conscious: The group discourse can talk about the existence of the group discourse itself and comment on its own characteristics.

Our sense of sustained time and the rhythms of life are largely reliant upon the narratives we tell ourselves (Bruner, 1990; Sarmiento, Trausan-Matu, & Stahl, 2005). We know that we have already lived through a certain part of the day or of our life because our present is located within a nexus of ties to the past or hopes for the future. In similar ways, a chat's web of references that connects current postings to prior ones to which they respond and to future postings that they elicit defines a temporality of the chat. This is experienced as a lived sense of time that is shared by the group in the chat. Like our individual internal clocks, the group temporality is attuned to the larger world outside—the world of family life that calls the students away from the chat for dinner or the world of school that interrupts a chat with class changes or homework pressures. The temporality that defines a dimension of the collaborative experience is constrained by the nature of the social situation and by the functionality of the technological environment.

Constructing the group experience

Groups constitute themselves (Garfinkel, 2006, pp. 189ff; Sacks, 1992, vol. I, pp. 144-149). We can see how they do this in the chat logs. At one level, the VMT service brings several students together and locates them in a chat room together. It may supply a math problem for them to work on and it may provide a facilitator who introduces them to the environment. At this point, they are a potential group with a provisionally defined membership. The facilitator might say something like, "Welcome to our first session of Virtual Math Teams! I am the facilitator for your session. . .. As a group, decide which question you would like to work on." (This is, in fact, part of the facilitator script from the session involving ImH and Jas excerpted above.) Here we can see that the facilitator has defined the group ("as a **group** ... **you**") and distinguished her own role as outside the group ("I am the facilitator ... **your** session"). The potential group projected by the facilitator need not necessarily materialize. Individual students may come to the setting, look around, decide it is lame and leave as individuals. However, this rarely happens. Sometimes an individual will leave without ever interacting, but as long as enough students come there, a group emerges.

Students enter the chat environment with certain motivations, expectations and experiences. These are generally sufficient to get the group started. One can see the group form itself. This is often reflected in the shift from singular to plural pronouns: "**Let's** get started. Let **us** do some math." We saw this in Avr's proposal: "I think **we** have to figure out the height by **our**selves." The proposal bid comes from an individual, but the projected work is for the group. Through her use of "we," Avr constitutes the group. Through her proposal bid, she constitutes the group as a recipient of the bid and elicits a response from them. Someone other than Avr must respond to the bid on behalf of the group. When Pin says, "I know how: draw the altitude," he is accepting Avr's proposal as a task for the group to work on and in so doing he makes a proposal about how the group should go about approaching this task (by making a geometric construction). In this interchange, the group (a) is projected as an agent ("we") in the math work (Lerner, 1993), and (b) is actually the agent of meaning making because the meaning of Avr's proposal is defined by the interaction within the group (e.g., by a math-proposal adjacency pair).

If the group experience is a positive one for the participants, they may want to return. Some chats end with people making plans to get together again. In some experiments, the same groups attended multiple sessions. We would like to see a community of users form, with teams re-forming repeatedly and with old-timers helping new groups to form and learn how to collaborate effectively.

The recognition that collaborative groups constitute themselves interactionally and that their sense making takes place at the group unit of analysis has implications for the design of cognitive tools for collaborative communities. The field of computer-supported collaborative learning (CSCL) was founded in the 1990s to pursue the analysis of group meaning making and the design of media to support it (Stahl, Koschmann *et al.*, 2006). We view the research described here as a contribution to this CSCL tradition.

We are designers of tools for collaborative groups. We want to design an online collaborative service, with strong pedagogical direction and effective computer support. Our goal is to design an environment that fosters exciting mathematical group experiences for students and inspires them to return repeatedly. Our ultimate vision is to foster a sustainable community of math discourse among students. We approach this by trying to understand how groups of students construct their experience in such settings.

When students enter our website now, they are confronted by a densely designed environment. The lobby to our chat rooms is configured to help students find their way to a room that will meet their needs. In the room, there is a daunting array of software functionality for posting and displaying chat notes, drawing geometric forms and annotating them, keeping track of who is doing what and configuring the space to suit oneself. There may be a statement of a math problem to solve or an imaginary world to explore mathematically. The service, problems and software are all designed to enhance the user's experience. But how can a student who is new to all this understand the meanings of the many features and affordances that have been built into the environment?

Groups of students spontaneously develop methods for exploring and responding to their environments. They try things out and discuss what happens. A new group may doodle on the whiteboard and then joke about the results. They bring with them knowledge of paint and draw programs and skills from video games, SMS and IM. The individuals may have considerable experience with single-user apps, but react when someone else erases their drawing; they must learn to integrate coordination and communication into their actions. The math problems they find in the chat rooms may be quite different from the drill-and-practice problems they are used to in traditional math textbooks and commercial "educational" software. It may take the group a while to get started in productive problem solving, so the group has to find ways to keep itself together and interacting in the meantime. There may be various forms of socializing, interspersed with attempts to approach the math. As unaccustomed as the math may be, the students always have some knowledge and experience that they can bring to bear. They may apply numerical computations to given values; try to define unknowns and set up equations; graph relationships; put successive cases in a table; use trigonometric relationships or geometric figures; draw graphical representations or add lines to an existing drawing. Mainly, they put proposals out in the chat stream and respond to the proposals of others. Sometimes the flow of ideas wanders without strong mathematical reflection. Other times, one individual can contribute substantial progress and engage in expository narrative to share her contribution with the group (Stahl, 2006a).

Groupware is never used the way its designers anticipated. The designers of VMT-Chat thought that its referencing tools would immediately clarify references to elements of drawings and transform chat confusion into logical threaded chat. But our studies of the actual use of these designed functions tell a quite different and more interesting story. The shared whiteboard with graphical references from the chat may allow more complex issues to be discussed, but they do not make pointing problem-free. We saw in a previous section how much work ImH and Jas engaged in to clarify for each other what they wanted to focus on. In the excerpt and in the longer chat, they used a variety of textual, drawing and referencing methods. Through this process, they learned how to use these methods and they taught each other their use. Within a matter of a fraction of a minute, they were able to reach a shared understanding of a topic to work on mathematically. During that brief time, they used dozens of deictic methods, some that would prove more useful than others for the future.

Chat is a highly constrained medium. Participants feel various pressures to get their individual points of view out there. In a system like VMT-Chat, there is a lot to keep track of: new postings, changes to the whiteboard, signs that people are joining, leaving, typing, drawing. Small details in how something is written, drawn or referenced may have manifold implications through references to present, past or future circumstances. Students learn to track these details; apply them creatively; acknowledge to the group that they have been recognized; check, critique and repair them. Each group responds to the environment in its own way, giving group meaning to the features of the collaborative world and thereby putting their unique stamp on their group experience.

In the process, they create a group experience that they share. This experience is held together with myriad sorts of references and ties among the chat postings and drawings. Often, what is not said is as significant as what is. Individual postings are fragmentary, wildly ambiguous and frequently confusing. In lively chats, much of what happens remains confusing for most participants. Clarity comes only through explicit reflections, up-takes, appreciations or probing. The interactions among postings, at many levels, cohere into a stream of group consciousness, a flow of collaboration, a shared lived temporality and, with luck, an experience of mathematical group cognition.

The small groups who meet in the VMT-Chat rooms participate in the larger collaborative communities of: the VMT project, the Math Forum user community and the math discourse community at large. In general, interacting small groups mediate between their individual members and the larger communities to which they belong. The discourse within the small group evokes and collects texts, drawings and actions by different participants, who bring multiple interpretive perspectives to the shared meaning making. Enduring ambiguity, mutual inconsistency and downright contradiction pervade the resultant group cognition, with its "inter-animation of perspectives" (Bakhtin, 1986; Wegerif, 2006). Whether or not we assume that an individual's thoughts are logically consistent and interpretively determinant, it seems that much of a group chat generally remains a mystery to both participants and researchers. Yet, from out of the shrouds of collective fog, insights are co-constructed that could not otherwise shine forth. The tension arising from conflicting or ungraspable interpretations in place of harmonious shared meaning fuels the creative work of constructing innovative group understanding.

The chat environment as incorporated in the VMT project is essentially different from familiar conversational situations, as we have seen in this paper. In general, there is little known by the participants about each other, except for what appears in the chat text or whiteboard drawings. No one's age, gender, appearance, accent, ethnicity is known. Even people's real names are replaced in the chat with anonymous login handles. Participants do not observe each other typing and correcting text until it is posted. Nor do they see what people are doing or saying in their lives outside the chat—if they have gone for a snack, are talking on the phone or are engaged in other, simultaneous online interactions. Normally, a person's history, culture and personality are conveyed through their vocal intonation and physical appearance (Bourdieu, 1972/1995); these are absent in chat. The one-hour duration of most VMT chats limits the history that can be established among participants through the available outlets of text and drawing, interaction style, word choice and use of punctuation. Yet, these drastically restricted means somehow allow incredibly rich, unique, creative and sophisticated interactions to take place. Insights take place and are shared; meaning is constructed and made sense of by groups. Perspectives and personal voices are established and acknowledged. Like characters in a Beckett play, chat participants learn to survive using radically impoverished discourse within a sensuously desolate landscape, and they sustain surprising forms of interaction for about an hour.

Conclusion

As we have seen in this paper, when students enter into one of our chats they enter into a complex social world. They typically quickly constitute a working group and begin to engage in activities that configure a group experience. This experience is conditioned by a social, cultural, technological and pedagogical environment that has been designed for them. Within this environment, they adopt, adapt and create methods of social practice for interacting together with the other students who they find in the chat environment. Over time, they explore their situation together, create shared meaning, decide what they will do and how they will behave, engage in some form of mathematical discourse, socialize, and eventually decide to end their session.

Then our job as researchers begins: to analyze what has happened and how the software tools we are designing condition, support and mediate the collaborative experiences that groups construct and sustain. We face the same poverty of knowledge about our subjects that the participants themselves face about each other. But, here too, less can be more. This record is conducive to careful, detailed analysis, without the interpretive complexities of video recording and transcription. We can analyze what happens at the group unit of analysis, with the methods of interaction adopted by the participants, because everything that could have gone into the shared understanding of the participants is available in the persistent record of the chat-room history.

We can study this record at our leisure and make explicit the influences that the group experienced tacitly in the flow of its life. We can observe how several students constitute and sustain their group cognition in the math chat environment we are designing with them. The group cognition persists in its record, indefinitely available for analysis.

We can identify successful and failed math proposals, questions, greetings and other low-level interactions. We can observe how groups construct, identify, make sense of and explore mathematical objects. But we can also see how these elementary interactions build up longer sequences of group cognition (Stahl, 2006b) [Investigation 22], intersubjective meaning making (Suthers, 2006) [Investigation 4] and sustained collaborative group experiences.

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15. Structuring Group Cognition

Abstract. This is an invited keynote talk that opened the International Conference on Computers and Education (ICCE 2009) on November 30, 2009, in Hong Kong, China. The intent of the talk was to provide a personal view of the field of computer-supported collaborative learning (CSCL) and to relate it to the Asia-Pacific audience. To do this, I tried to describe—in an informal tone—the approach I was taking to analyzing online interaction in small groups. In publishing the talk, I have tried to retain its original tone.

The field of CSCL is particularly interested in the ways small groups can build knowledge together thanks to communication and support from networking technology. I hope that CSCL environments can be designed that make possible and encourage groups to think and learn collaboratively.

In my research, my colleagues and I look at logs of student groups chatting and drawing about mathematics in order to see how they build on each other's utterances to achieve more than they would individually. To answer this important question, we must look carefully at the details of discourse in CSCL groups and develop innovative tools and theories. In this Investigation, I outline methods and levels of analysis that have resulted in the findings reported in the Virtual Math Teams research cited in the references.

Keywords. Event, session, theme, discourse move, adjacency pair, utterance, reference.

"Learning without thought is labor lost;
thought without learning is perilous."
-- Confucius 孔丘 Kong Qiu

Views of Learning and Thinking

About 2,600 years ago, Confucius viewed *learning* and *thinking* as belonging together.

The learning sciences of the twenty-first century agree with Confucius on this point. They view learning as involving meaning making by the learners (Stahl, Koschmann & Suthers, 2006). Students who just passively accept instruction without thinking about it and coming to understand it in their own way of making sense of things will be wasting everyone's time. Why? Because they will not be able to *use* the new knowledge or to *explain* it. Of course, this construction of meaning takes place over time: someone can learn something one day and make sense of it later, when they try to use it in different circumstances and to explain their use to other people and to themselves. But if they never integrate what they have learned into their own thinking and acting—by applying it where appropriate and talking about it clearly—then they will not have really learned anything important.

What sociologists of small groups like Bernstein, as presented in Hasan's overview (1999), know about social interactions and contribute to our understanding of the significance of group cognition is the way participants internalize the resources that evolve within one interactional context and then recontextualize them in the new and radically different contexts they find themselves in later. In this way, the new knowledge that is created, or the new or enhanced knowledge-building skills that are appropriated, can replicate and spread contagiously. It is the magic that, for instance, makes seemingly inconsequential interactions between mothers and children while cleaning the oven play a key role in a child's preparation for schooling (Cloran, 1999). It is precisely because of the tremendous impact the results of these interactions can have going forward that the local sacrifice that may occur in terms of efficiency of the interaction can be viewed as a small price to pay when one considers the long-term cost-benefit ratio, the profound impact of one transformational experience of group cognition.

Vygotsky *(1930/1978)* made an even stronger argument. He showed for the major forms of human psychological functioning that these individual capabilities were derived from experiences of interactions between people:

> *An inter-personal process is transformed into an intra-personal one.* Every function in the child's cultural development appears twice: first, on the social level

> and later, on the individual level; first *between* people (*inter-psychological*), and then *inside* the child. This applies equally to voluntary attention, to logical memory, and to the formation of concepts. All the higher functions originate as actual relations between human individuals. (p. 57)

Although all functions of individual cognition are derived from group cognition, the reverse is not true. As Hutchins (1996) demonstrated with his example of the bridge of a large Navy ship, not all group cognition can be internalized by an individual: "The distribution of knowledge described [in the book] is a property of the navigation team, and there are processes that are enabled by that distribution that can never be internalized by a single individual" (p. 284). Whether or not specific skills and knowledge can be mastered by individuals or only by teams, the learning of those skills or knowledge seems to rely heavily and essentially on group cognition. That is why we try to study and to promote group cognition.

What we, as learning scientists, have learned about learning and thinking in recent decades in the West is influenced by what philosophers before us said. For instance, most Western philosophers until the middle of the 1900s thought that knowledge could be expressed by propositions, sentences or explicit statements. If that were true, then the learning of knowledge could, indeed, consist simply of students individually hearing or reading the right sentences and remembering them.

However, Ludwig Wittgenstein's book, *Philosophical Investigations*, published in 1953, questioned this view of learning and thinking. It looked at math as a prime example. Mathematical knowledge can be seen as a set of procedures, algorithms or rules. Wittgenstein asked how one can learn to follow a mathematical rule (Wittgenstein, 1944/1956, Part VI; 1953, §185-243, esp. §201). For instance, if someone shows you how to count by fours by saying, "4, 8, 12, 16," how do you know how to go on? Is there a rule for applying the rule of counting by fours? (Such as, "Take the last number and add 4 to it.") And if so, how do you learn to apply *that* rule? By another rule? Eventually, you need to know how to do something that is not based on following a propositional rule—like counting and naming numbers and recognizing which numbers are larger. The use of explicit rules must be somehow grounded in other kinds of knowledge. Wittgenstein's question brought the logical view of knowledge as explicit propositions into a paradox: if knowledge involves knowing rules, then it must involve knowing how to use rules, which is itself *not* a rule. These other kinds of knowing include the tacit knowledge of how to behave as a human being in our culture: how to speak, count, ask questions, generalize, put different ideas together, apply knowledge from one situation in another context and so on. *And these are the kinds of things that one initially learns socially, in small groups or in child-parent dyads.* In the theory of group cognition, we identify many of these non-propositional ways of knowing as practices. We study how groups adopt group practices, which may become personal habits or skills of the group participants [Investigation 16].

Wittgenstein was an unusual philosopher because he said that problems like this one could not be solved by contemplation, but rather by looking at how people actually do things. He said, "Don't think, look!" (1953, §66). In studying group cognition, I try to follow Wittgenstein's advice. I try to view how people actually *do* things. Rather than telling you what my *views* or ideas are about learning and thinking in CSCL groups, I want to *show* you how I *view* or observe learning and thinking in CSCL groups.

The term "view" in the title of my talk has this double meaning: it means both viewing by looking at something with my eyes and also viewing in the metaphorical sense of thinking about something from a conceptual perspective. The Greek philosopher, Plato, who lived at about the same time as Confucius, made this metaphor popular in Western thought (Plato, 340 BCE/1941).

Although Wittgenstein himself did not actually look at empirical examples of how people follow rules in math, we can. By carefully setting up a CSCL session, we can produce data that allows us to view small groups of students learning how to follow math rules and thinking about the math rules. This is what I do to view learning and thinking in CSCL groups. It is the basic approach of the science of group cognition (Stahl, 2009) that I want to describe today.

The work of our research team and other colleagues involves looking closely at some rich examples of student groups learning and thinking about math. I would like to share a brief excerpt from one of these examples with you and talk about how we go about viewing the learning and thinking of this group of students. In particular, how do they construct their group cognition through collaborative meaning-making activities?

In this Investigation, we will look at the meaning-making work of a group of students, analyzing their language-based interaction at multiple levels:

- The overall *event*,
- A specific hour-long *session* of the two-week event,
- A discussion *theme* that arose in the session,
- A discourse *move* that triggered that theme,
- A pivotal *interchange* that carried out the discourse move,
- A single *utterance* that was part of the interchange and
- A particular *reference* in the utterance.

By looking at the linguistic connections, we can see how the syntax, semantics and pragmatics weave a network of meaningful references that accomplishes a set of cognitive achievements by the group interaction.

On the one hand, we can see the linguistic elements of a log of discourse and their structure of temporal and hierarchical relationships as accomplishing group cognition by, at each moment, constraining the next utterance as situated in the context of event, session, theme, discourse moves, eliciting adjacency pairs, preceding utterances and network of references. On the other hand, human actors creatively design accountable responses within the constraining situation defined by these contextual elements. That is, among the constraints on the actors is the requirement that their linguistic actions make sense in the on-going discourse and that they reveal their meaning and relevance in their linguistic design.

Although people often design their utterances to convey the impression that they are the result of psychological processes (change of mental state, expression of internal reflections), we can analyze the group cognition in terms of the linguistic effects of the observable words and drawing actions, without making any assumptions about individual mental representations. The individual students are active as linguistic processors—interpreting and designing the utterances—but the larger mathematical and cognitive accomplishments are achieved through the group discourse, which exists in the computer displays, observable by the students and—even years later—observable in the logs by analysts. We can see and make explicit how teams become teams in the ways that they manifest the contingencies and accountabilities of their unique situation, using conventional linguistic structures as resources.

The work of the Virtual Math Teams (VMT) research team—which I directed from 2003-2014—and collaborating researchers involves looking closely at some rich examples of student groups learning and thinking about math. I would like to share a brief excerpt from one of these examples with you and talk about how we go about viewing the learning and thinking in this group of students.

An Example of Learning and Thinking

I will now describe an illustrative event, session, theme, move, interchange, utterance and reference from the work of a VMT group of students.

The event: VMT Spring Fest 2006 Team B

Here, we will be talking about an online event that occurred several years ago. The interaction is preserved in a computer log, which can be replayed by researchers and is partially presented in this Investigation. Three students, probably about 16 years old, were assigned to form Team B, and they met with a facilitator in an online chat environment on May 9, 10, 16 and 18, in 2006, for about an hour in the late afternoon each day. The participants were distributed across three time zones in the US. The event was part of the VMT research project. Neither the students nor we know anything more about each other's personal characteristics or background.

The topic for this event was to explore a pattern of sticks forming a stair-step arrangement of squares (see Figure 1) and then to explore similar patterns chosen by the students themselves. (A subsequent session by the same students is discussed in Investigation 23.)

Session I

1. Draw the pattern for N=4, N=5, and N=6 in the whiteboard. Discuss as a group: How does the graphic pattern grow?

2. Fill in the cells of the table for sticks and squares in rows N=4, N=5, and N=6. Once you agree on these results, post them on the VMT Wiki

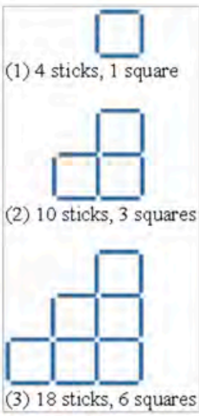
3. Can your group see a pattern of growth for the number of sticks and squares? When you are ready, post your ideas about the pattern of growth on the VMT Wiki.

Sessions II and III

1. Discuss the feedback that you received about your previous session.

2. WHAT IF? Mathematicians do not just solve other people's problems—they also explore little worlds of patterns that they define and find interesting. Think about other mathematical problems related to the problem with the sticks. For instance, consider other arrangements of squares in addition to the triangle arrangement (diamond, cross, etc.). What if instead of squares you use other polygons like triangles, hexagons, etc.? Which polygons work well for building patterns like this? How about 3-D figures, like cubes with edges, sides and cubes? What are the different methods (induction, series, recursion, graphing, tables, etc.) you can use to analyze these different patterns?

3. Go to the VMT Wiki and share the most interesting math problems that your group chose to work on.



N	Sticks	Squares
1	4	1
2	10	3
3	18	6
4	?	?
5	?	?
6	?	?
...	...	...
N	?	?

Figure 1. Topic for VMT Spring Fest 2006.

The VMT online environment consisted primarily of a synchronous chat window and a shared whiteboard. At the end of each session, the students were supposed to post their findings on a wiki, shared with other teams participating in the Spring Fest. Between sessions, the facilitator posted feedback to the students in a textbox on the whiteboard.

The session: Session 3, May 16, 7:00-8:00 pm

Let's look at an excerpt from the end of the third session. The three students had already solved the original problem of the stair-step pattern of squares. They had also made up their own problem involving three-dimensional pyramids. Now they turned to look at the problem that Team C had described on the shared VMT wiki after session 2. Team B is looking at an algebraic expression that the other team of students had derived for a diamond pattern of squares. They start to draw the pattern in their whiteboard (see Figure 2) and chat as a team about the problem of this new pattern.

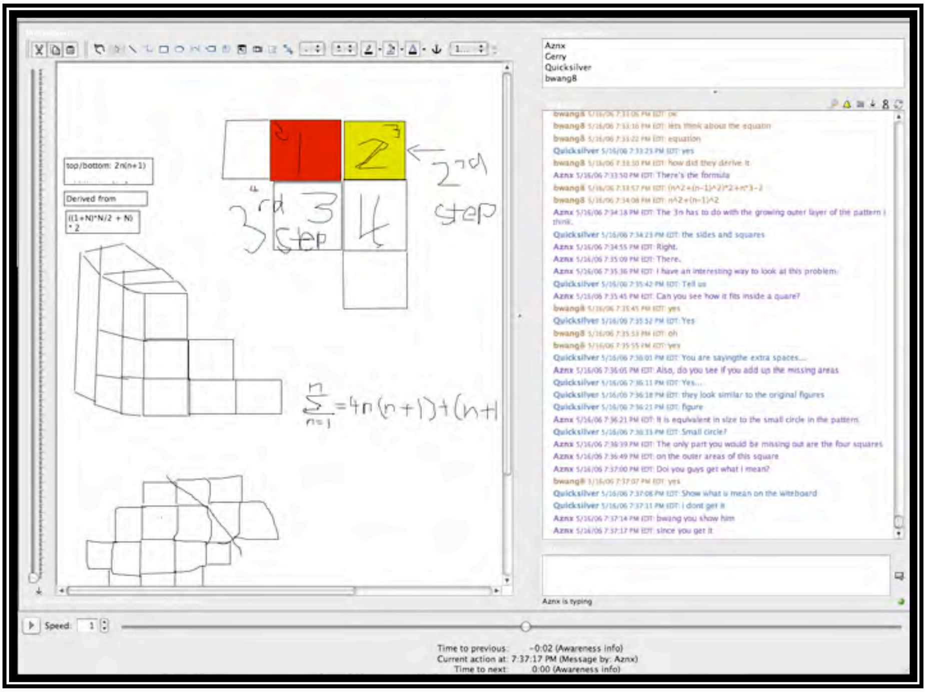


Figure 2. The VMT Replayer showing the VMT online environment.

The theme: "I have an interesting way to look at this problem"

One of the students, Aznx, begins to make a proposal on how to "look" at their problem. First, he announces, "I have an interesting way to look at this problem." Note that he uses the word "look" in the same double meaning of "view" that was mentioned above. As we will see, he means he has a new way to think about the problem mathematically—and that involves a way of observing a visual image of the problem. The group does its thinking both by typing text or algebraic expressions in the chat window and by simultaneously drawing and viewing diagrams or geometric constructions of the problem in the shared whiteboard (see Çakir, Zemel & Stahl, 2009 [Investigation 12], for an analysis of the coordination by the group of their text, symbols and drawings).

Aznx' announcement opens an opportunity for the group to discuss a way of looking at the problem. In fact, the group takes up the offer that is implicit in Aznx' statement and the students spend the next eight minutes trying to each understand it. As it turns out, they will work on this view of the problem for the rest of this session and most of their final session.

A VMT chat session can generally be analyzed as a series of themes or discussion topics. Often, themes come and go, and different themes overlap, with one wrapping up while another gets started. Researchers can identify the boundaries of a theme: when a new theme opens and an old one closes (Zemel, Xhafa & Çakir, 2009).

In this case, the group has been talking about how the diamond pattern grows as a geometric figure for a couple of minutes and then they discuss Team C's algebraic expression for a couple of minutes. As those themes get played out and there is a pause in the chat, Aznx makes a move to open a new theme for the group.

A move: Showing how to view the problem

Aznx' announcement that he has a perspective to share with the group is a way of introducing a new theme, a "pre-announcement" (Schegloff, 2007, pp. 37-44; Terasaki, 2004). Conversations often flow by new contributions picking up on something that was already being discussed. Online text chat tends to be more open than face-to-face talking; chat does not follow the strict turn-taking rules of conversation. However, it is still common to do some extra work to change themes even in chat. In a sense, Aznx is asking permission from the group to start a new theme. Quicksilver responds encouragingly right away by saying, "Tell us" (see Figure 3).

line	date	start	post	delay		
919	5/16/06	19:35:26	19:35:36	0:00:06	Aznx	I have an interesting way to look at this problem.
920	5/16/06	19:35:41	19:35:42	0:00:03	Quicksilver	Tell us
921	5/16/06	19:35:38	19:35:45	0:00:00	Aznx	Can you see how it fits inside a quare?
922	5/16/06	19:35:45	19:35:45	0:00:07	Bwang	yes
	5/16/06	19:35:49	19:35:52	0:00:00	Bwang	[user erased message]
923	5/16/06	19:35:51	19:35:52	0:00:01	Quicksilver	Yes
924	5/16/06	19:35:52	19:35:53	0:00:02	Bwang	oh
925	5/16/06	19:35:55	19:35:55	0:00:06	Bwang	yes
926	5/16/06	19:35:53	19:36:01	0:00:04	Quicksilver	You are sayingthe extra spaces...
927	5/16/06	19:35:58	19:36:05	0:00:06	Aznx	Also, do you see if you add up the missing areas

Figure 3. The move to introduce Aznx' new way of looking at the group's problem. (This log for analysis encodes the chat stream and associated awareness messages about when people started typing, along with timing data to reflect the flow of discourse.)

Actually, Aznx already starts typing his proposal before he gets Quicksilver's response, but it is not posted until afterward. The next step in his proposal is: "Can you see how it fits inside a square?" Here, he structures his contribution as a question, which elicits a response from the other members of the team. Note that he uses the term "see" in his proposal with the same double meaning as the term "look" in his prior announcement. As we shall see (in both senses), the group tries to work out and comprehend Aznx' proposal both conceptually and visually.

Both Bwang and Quicksilver respond to Aznx's proposal with "Yes." However, both modify this response. Bwang starts to type something else, but erases it; then he posts two messages: "oh" and "yes." This suggests some hesitation in responding to the proposal immediately. Quicksilver follows his initial positive response with, "You are saying the extra spaces …" He is asking for more clarification of the proposal. While Quicksilver is typing his request for clarification, Aznx is typing an expansion of his initial proposal: "Also, do you see if you add up the missing areas …"

The analysis of interaction moves is central to the science of group cognition. This is the level of granularity of many typical group-cognitive actions. Discourse moves are ways in which small online groups get their work done. They often follow conventional patterns—speech genres (Bakhtin, 1986) or member methods (Garfinkel, 1967)—which makes them much easier for participants to understand. Researchers can also look for these patterns to help them understand what the group is doing.

In this case, a new theme is being opened, one that will provide direction for the rest of this group's event together. This move is an example of one way in which a group can establish a shared understanding of a diagram or select a joint problem conceptualization (depending on how we take the terms "look" and "see"). Other moves that we often see in VMT logs are, for instance, defining shared references, coordinating problem-solving efforts, planning, deducing, designing, describing, solving, explaining, defining, generalizing, representing, remembering and reflecting as a group.

An interaction: Question/response: "Can you see how it fits inside a square?" / "Yes"

Interactions involve two or more people responding to each other. In conversation analysis, one typically looks for well defined "adjacency pairs" (Duranti, 1998; Sacks, 1965/1995; Schegloff, 2007) as forms that interactions often take. A prototypical adjacency pair is question/answer. Aznx' offering of a question— "Can you see how it fits inside a square?"—followed by Bwang and Quicksilver's responses— "yes," "Yes"—illustrate this structure for the simplest ("preferred") case: one person poses a yes/no question, and the others respond with an affirmative answer.

Response structures of interactions are often more complicated than this. Text chat differs from talk in that people can be typing comments at the same time; they do not have to take turns and wait until one person stops talking and relinquishes the floor. They will not miss what the other person is saying, because unlike with talk, the message remains observable for a while. The disadvantage is that one does not observe how people put together their messages, with pauses, restarts, corrections, visual cues, intonations and personal characteristics. While it is possible to wait when you see that someone else is typing a message,[9] people often type simultaneously, so that the two normal parts of an adjacency pair may be separated by unrelated postings. For example, Quicksilver's question (line 926 in Figure 3) separated Aznx's continuation of his line 921 posting in line 927, because 926 appeared before 927 although 927 was typed without seeing 926. So, in chat we might call these "response pairs" rather than "adjacency pairs." While they may be less sequentially *adjacent* than in talk, they are still direct *responses* of one posting to another.

Because the sequencing in online chat texting is less tightly controlled than in face-to-face talk, response pairs are likely to become entangled in the longer sequences of group moves. This may result in the common problem of "chat confusion" (Fuks, Pimentel & Pereira de Lucena, 2006; Herring, 1999). It can also complicate the job of

[9] The VMT environment displays an awareness message under the chat tab when someone is typing. The content being typed is not displayed to other participants until the message is posted to the chat. See Figure 2 or 5.

the researcher. In particular, it makes the task of automated analysis more complicated. In convoluted chat logs, it is essential to work out the response structure (threading) before trying to determine the meaning making. The meaning making still involves participants interacting through the construction of response pairs, but in chat people have to recreate the ties among these pairs. Realizing this, the group members design their postings to be read in ways that make the response pair or threading structure apparent, as we will see (for more discussion of this, see Zemel & Çakir, 2009).

An utterance: Question: "Can you see how it fits inside a square?"

In his posting— "Can you see how it fits inside a square?"—Aznx is comparing the relatively complicated diamond shape to a simple square. This is a nice strategy for solving the group's problem. The group can easily compute the number of stick squares that fill a large square area. For instance, if there are five little squares across the width of a square area (and therefore five along the height), then there will be five-squared, or 25 little squares in the area. In general, if there are N little squares across the width, there will be N-squared to fill the area. This is a strategy of reducing the problem to a simple or already known situation—and then perhaps having to account for some differences. So Aznx' posting seems to be relevant to thinking about the math problem conceptually.

At the same time, Aznx poses his proposal in visual or graphical terms as one of "seeing" how one shape "fits inside" of the other. The group has been looking at diagrams of squares in different patterns, both a drawing by Team C in their wiki posting and Team B's own drawings in their whiteboard. So Aznx's proposal suggests visualizing a possible modification to one of the diamond drawings, enclosing it in a square figure (see the blue diamond pattern enclosed in the red square in Figure 4). He is asking the others if they can visualize this also, so that the group can use this to simplify and solve their problem with the diamond.

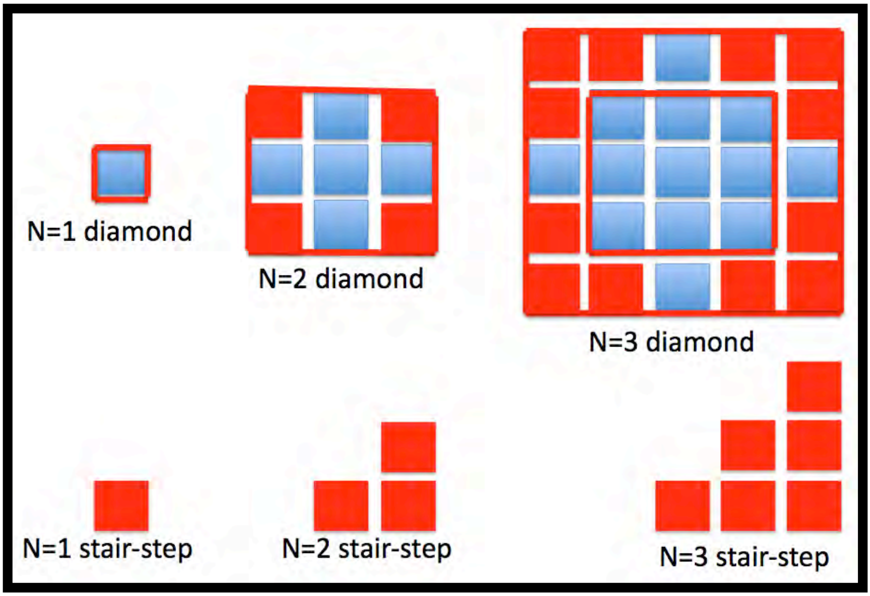


Figure 4. Blue diamond patterns and red stair-step patterns.

Aznx presents his proposal about re-thinking the problem as a question about visualizing the diagram. The group has been working in the VMT environment, going back and forth between text in the chat area and drawings in the whiteboard. They have started with problems presented graphically and have discussed these graphical problems in their text chat. They have shared different ways of viewing the relationships within the drawings and they have gradually developed symbolic algebraic ways of expressing general relationships about patterns in these drawings, working out these symbolic expressions in the chat and then storing them more persistently in the whiteboard.

We have been calling Aznx' chat posting a "problem-solving math proposal" (Stahl, 2006a, chapter 21). However, it is presented in the grammatical form of a *question*. Aznx did not simply state a proposal like, "I think we should enclose the diamond in a square, calculate the size of the square and then subtract the missing areas." Rather, he first announced that he had "an interesting way to look at this problem" and then explained his way of looking by asking if the others could "see how it fits inside a square." Presenting a proposal calls on the others to accept the proposal and to start to work on it. Of course, the others can reject the proposal, ask for clarifications about it, make a counterproposal or ignore the proposal.

But Aznx' utterance is not a full proposal that the others must accept or reject. It is another preliminary step. It asks the others if they can visualize something. It puts this to them as a question. If they say yes, then Aznx can proceed to make his proposal—or perhaps the others will see the implications of his way to look at the problem—what makes it "interesting"—and propose the strategy without Aznx having to advocate it, explain it and defend it. If they say no—that they cannot see how it fits inside a square—then he can explain his view further so they will be better prepared to accept his proposal.

Aznx' chat posting avoids articulating a complete proposal; by starting the conversation about the visualization, it involves the others in articulating the proposal *collaboratively*. In fact, in the subsequent discussion, the others do "see" the strategy that is implicit in Aznx' interesting view of the problem and they do help to articulate the strategy and then pursue it. By designing his proposal as this preliminary question about viewing the problem, Aznx succeeds in directing the group problem solving in a certain direction without his having to fully work out a detailed, explicit proposal. Aznx does not seem to be presenting a solution that he has worked out in his head. Rather, he is presenting his "interesting idea" for an approach to solving the problem so that the group will proceed to use the idea and work as a group to try to solve the problem with this approach.

A reference: "It"

Aznx' question is ambiguous at a purely syntactic level. It asks the others, "Can you see how it fits inside a square?" To what does the term "it" refer? People use pronouns like "it" rather than lengthy explicit noun phrases when the reference is clear from the context. This situates the utterance in its context—its meaning cannot be gathered from the utterance considered in isolation. Often, "it" will reference something that was recently referred to in a previous contribution that the new utterance is building on. For instance, "it" could refer to something mentioned in Aznx' previous utterance, "I have an interesting way to look at this problem." But to say that "it" refers to "this problem" does not make complete sense. The *problem* does not fit inside a square.

However, a minute earlier, when the group was discussing Team C's equations, Aznx said about part of an equation, "The 3n has to do with the growing outer layer of the pattern I think." He was referencing different aspects of the growth of the diamond pattern, particularly its "outer layer." Therefore, when he announces that he has an interesting way to view the problem, it is reasonable to assume that his new way of looking may be closely related to the observation that he had just reported about the outer layer of the diamond pattern. Because everyone in the group was following the flow of the discussion, Aznx could refer to the topic of the outer layer of the diamond pattern in the shorthand of the pronoun "it." When he typed, "Can you see how it fits inside a square?" he could assume that the readers of this posting would understand that he was referring to how some aspect of the diamond pattern can be seen as fitting inside of some square shape.

Although the reference to some aspect of the diamond pattern is relatively clear, the details are not clear about just what aspect of the diamond is to be visualized or focused on visually, where a square is to be constructed, and how the diamond fits inside the square. At this point, only a rather confusing image of a diamond pattern is visible on the whiteboard (see Figure 2). To *make sense* of "it," everyone has to follow the flow of discussion and the way in which the math topic is being developed as part of a "joint problem space," understood and visualized by the whole group.

Bwang and Quicksilver both respond initially to Aznx' question with "Yes." However, as we saw, Bwang indicates some hesitancy in his response and Quicksilver asks for further clarification. Aznx and Quicksilver discuss what they see when they fit a diamond pattern inside a square. Quicksilver notes that the "extra spaces" (colored red in Figure 4) look similar to the stair-step pattern that the team worked on previously. But Aznx goes on to talk about the four squares on the outer areas of the square, confusing Quicksilver. That is, as they each try to work out the details of Aznx' view, they display that they are not *seeing* things quite the same way. They have not yet achieved an adequate shared understanding or shared view.

Quicksilver suggests that Aznx show what he means on the whiteboard, so the ambiguity of his proposal can be resolved. Rather than drawing it himself, Aznx asks Bwang to do a drawing, since Bwang said he could see what Aznx was talking about. Bwang has in the past shown himself to be skilled at making drawings on the whiteboard, while Aznx has not tried to draw much.

Bwang draws a very clear diagram on the whiteboard for the diamond pattern when N=2 (see Figure 5). As soon as Bwang completes his drawing, he makes explicit the problem-solving proposal that is implicit in Aznx' way of viewing the problem or the pattern: "We just have to find the whole square and minus the four corners." His drawing has made this process very visible. He drew the diamond pattern with white squares and then filled in a large square that the diamond fits into by adding red squares. The red squares fill in symmetrical spaces in the four corners of the diamond pattern. The group can now look at this together in the shared whiteboard, providing a shared view of the matter to the group.

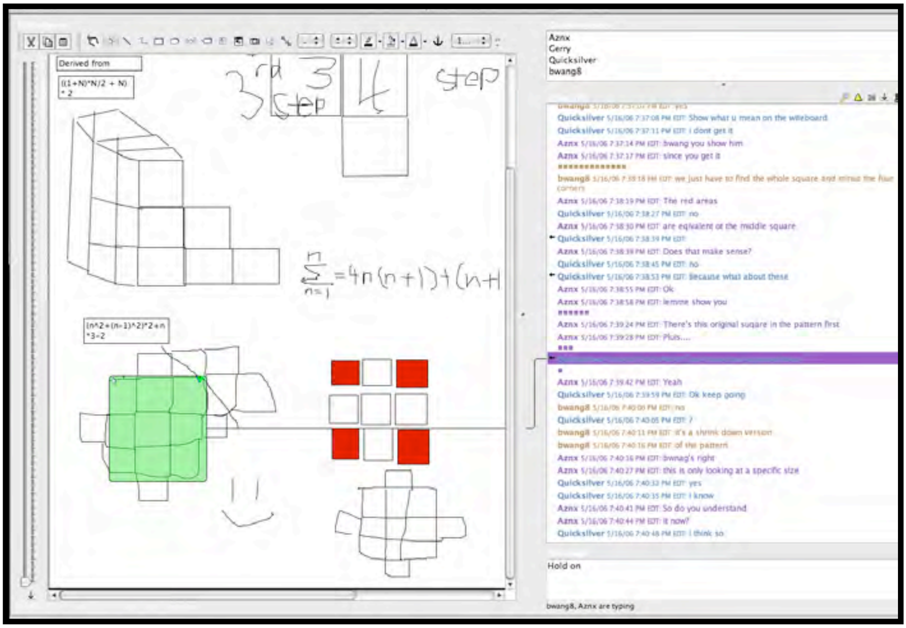


Figure 5. Bwang has drawn the white diamond for N=2 with red squares filling in the corners of an enclosing square. Quicksilver is pointing to a diamond pattern for N=3, also re-drawn lower on the whiteboard.

The group then discusses the view of the diamond pattern fitting into an enclosing square. They eventually realize that some of their observations are only true for the diamond pattern at a certain stage, like N=2.

So Bwang then draws the pattern for N=3. Here it starts to become visible to the group that the red squares in each corner follow the stair-step pattern (see Figure 6).

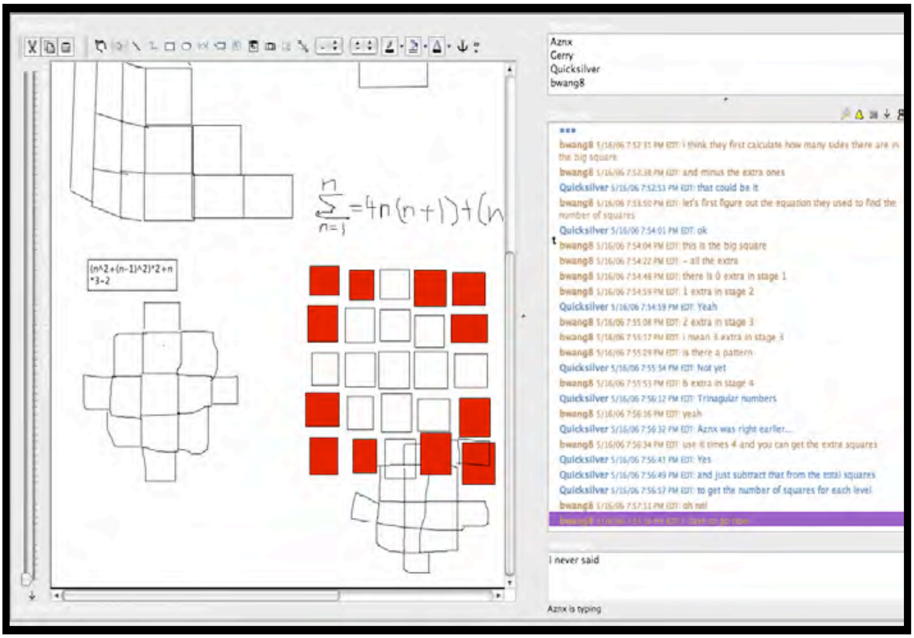


Figure 6. Bwang expanded his drawing to make the diamond for N=3. Note the red corners are now stair-step patterns.

The group has realized that viewing a graphical image of a mathematical pattern can be very helpful in thinking about the pattern. They treat the whiteboard as a shared, viewable image of aspects of the joint problem space of their collaborative work. Viewing this image and pointing out elements of it ground their chat discourse.

However, the image drawn by Bwang captures just one particular stage in the pattern, one value of N. They then start to look at images for different values of N or different stages in the growing pattern. They count the number of red squares in a corner as N increases and notice that it goes: 0, 1, 3, 6 (see Figure 4). This pattern is familiar to them from their earlier analysis of the stair-step pattern. They call this sequence "triangular numbers," from Pascal's triangle, which is often useful in combinatorics math problems. They know that this sequence can be generated by Gauss' formula for the sum of the consecutive integers from 1 to N: (N+1)N/2. Unfortunately, at that point Bwang has to leave the group. But when they return in session 4, they will quickly put together the simple formula for the enclosing square minus this formula for the number of squares in each of the four corners, to solve their problem.

Viewing the Learning and Thinking

Let us pause now from all these details about the case study of three students in a VMT session and talk about how we view learning and thinking in CSCL groups. I have tried to demonstrate how we view learning and thinking in CSCL groups by *viewing* with you how a group of three students engaged in collaborative thinking and learning processes within an online environment for drawing and chatting.

We went through several levels of analysis of the group discourse (see Figure 7). We started by mentioning the overall context of the *event*. This was an online event in which Team B, consisting of three students, met in the Virtual Math Teams environment to discuss patterns of squares formed by sticks. We then focused on the smaller *session* unit, looking at Team B's third session, in which they considered a pattern that another group, Group C, had analyzed. Within this session, we identified one of several *themes* of discussion in that session, namely the one involving Aznx' "interesting way to look at this problem."

Event:	VMT Spring Fest 2006, Team B
Session:	session 3, May 16, 7:00-8:00 pm
Theme:	"I have an interesting way to look at this problem"
Move:	Show how to view
Pair:	"Can you see how it fits inside a square?" "Yes"
Utterance:	"Can you see how it fits inside a square?"
Reference:	"it," diamond pattern

Figure 7. Levels of analysis of online group discourse.

Aznx introduced the theme by initiating a group problem-solving *move*. Namely, he got the group to view the problem in a certain way, as a diamond enclosed in a square. We saw how the group ended up drawing images in their shared whiteboard of diamond patterns enclosed in squares. Aznx introduced this group move in a subtle way; he did not simply come out and say, "We should analyze this pattern as partially filling an enclosing square." Rather, he first announced that he had an interesting view, involving the others in his approach to make it a group problem-solving process. Then he asked if the others could view the problem in a certain way. He did this through a question/answer response *pair*: he asked a question, which elicited a yes-or-no response from the others. By eliciting the response, he oriented the others to look at the diagram in the whiteboard in a certain way—namely in the way that his question implicitly proposed. A set of lines on the whiteboard are not immediately meaningful—they must be seen (interpreted) *as* something (Heidegger, 1927/1996, §32; Wittgenstein, 1953, §II xi).

Aznx' formulation of his question looks like a simple *utterance* in question format, but it entails selection from a number of different ways of picturing the relationships among the diamond pattern, the enclosing square and the empty corners. To begin with, one must decide what the *reference* to "it" is doing.

Indexical references like the pronoun "it" are ubiquitous in online text chat—and unavoidable according to Garfinkel (1967) [see Investigation 5]. They require the reader to understand or reconstruct the implicit threading or response structure of the chat. The difficulty of doing this often leads to confusions, which require the participants to spend time clarifying the content and structure of their discussion. For instance, in our example of the move of seeing the diamond in the square, the group had to engage in a couple minutes of chatting and drawing to co-construct a shared understanding of the problem.

Issues of shared understanding can be analyzed as linguistic problems of reference. In other words, in order to view learning and thinking in CSCL groups, we do not try to figure out what is going on in the heads of the students; rather, we try to figure out what is going on in their chat postings and their drawing actions. This is what we call the group's *interaction*. In VMT, the interaction of the virtual math team consists of sequences of chat postings and drawing actions.

Our first step in figuring out what is going on in the chat postings and drawing actions is generally to try to analyze the sequencing of these by reconstructing their response structure—what previous action each new action is responding to and what kinds of action it is eliciting, what it is opening up an interaction space for, or what kinds of responses it is making relevant as next postings. Often, this leads to some kind of threading diagram (Çakir, Xhafa & Zhou, 2009), uptake graph (Suthers, Dwyer, Medina & Vatrapu, 2010b), or interaction model (Wee & Looi, 2009). This represents graphically a basic structure of the meaning-making sequencing. Then we try to understand what problem-solving work is being accomplished at each point in the sequence. This involves looking at different levels of granularity, such as the event, session, theme, move, pair, utterance and reference. Understanding the meaning that the group is co-constructing in their interaction generally involves going back and forth through these different levels and integrating partial interpretations from the different levels in a dialectic of whole and part (Gadamer, 1960/1988).

Through this process, we can gradually view the learning and thinking that takes place in the CSCL group. This learning and thinking is not something that takes place primarily in the minds of the individual participants (although the individuals in the group are each continuously using their linguistic skills to understand what is going on and to respond to it with their postings and drawings). Rather, when there is an intense collaborative process taking place in the online environment, the thinking and learning takes place in the visible text and graphical interactions.

According to the theory of group cognition, thinking in a CSCL collaborative interaction does not take place so much the way we usually think of thinking. Thoughts, or cognitive processes, are not characterized in terms of neurons connecting and firing in a brain; they are analyzed in terms of text postings and drawings referring to each other and building on each other, in the spirit of the idea of transactivity. We will look more at how this takes place in a minute. Similarly, learning does not take place the way we learned about learning. It is not viewed as a change in the amount of knowledge stored in a brain. Rather it is described as a matter of knowledge artifacts being gradually refined through sequences of text postings and graphical drawings that are interrelated and that explicate each other. The knowledge artifacts may be statements about a problem the group is working on, as viewed from a new perspective that the group has developed. The knowledge artifact might be a drawing like Bwang's in Figure 6 or an algebraic formula that sums up the group's analysis of pattern growth.

Unpacking the Group Learning and Thinking

Rather than talking about learning and thinking in the abstract, let us unpack some more how learning and thinking take place in Team B's interaction—in their text chatting and drawing together. Let's go back through the hierarchy of levels of analysis *in the opposite order* to say something about how references, utterances, response pairs, moves, themes, sessions and events can contribute to learning and thinking in CSCL groups (see Figure 8).

Reference: network of meaning, indexical ground, joint problem space

Utterance: recipient design for reading's work

Pair: projection and uptake

Move: getting the problem-solving work done

Theme: coherent interactional sequences

Session: temporal structuring and re-member-ing

Event: forming groups and co-constructing knowledge objects

Figure 8. Levels of learning and thinking in online group discourse.

Reference: Network of meaning, indexical ground, joint problem space

When one studies logs of virtual math teams, one sees that they spend a lot of time reaching shared understanding about references in their postings. Elsewhere, I review an example of this from Team B's session four, where Aznx, Quicksilver and Bwang get quite confused about references from the chat to different equations written on the whiteboard (Stahl, Zemel & Koschmann, 2009).

The reason that people devote so much time and energy to resolving confusing references is that the network of references that they build up together plays an extremely important role in their group learning and thinking. In the theory of CSCL, there is considerable emphasis on the ideas of "common ground" (Clark & Brennan, 1991) and "joint problem space" (Teasley & Roschelle, 1993). A group establishes common ground largely by reaching a shared understanding of how references work in their discourse. As it interacts over time, a group co-constructs a network of references that can become quite complex (Sarmiento & Stahl, 2008).

This network of references defines the context or situation in which the group discourse continues to take place. Aznx' reference to "it" that we looked at contributed to a network of meaning that the group built up continuously through their interaction. This network included images of sticks in various patterns (like diamonds at stage N=2 and N=3), the relationships of the patterns (like a diamond enclosed in a square with stair-step empty corners), concepts referred to by technical terms (like "triangular numbers" or "summation"), and symbols representing mathematical operations (like equations for number of squares in a pattern).

As a group builds up its network of shared references, it can use more shortcut references to point to things without creating confusion. People can use deictic references to point to things in the network, like "this formula," "the second equation," or "it." In linguistic terms, the shared network of references provides a background for referring to things, a so-called indexical ground of deictic reference (Hanks, 1992).

In problem-solving terms, the network of references forms a joint problem space, a shared view of the topic that the group is addressing (Sarmiento & Stahl, 2008). For Team B, the joint problem space starts with the stair-step pattern and the chart of the number of sticks and squares for each stage of this pattern as presented in the topic description for the event. By the middle of session 3, it includes the diamond pattern and the view of "it" enclosed in a square, forming empty corners. It also includes triangular numbers and their associated formula, as well as several other equations from Team C and from Team B's own work. The team's interaction (the text postings and drawings) gradually creates this joint problem space and is situated within it. The work and utterances of the team can only be understood (by the participants and by us as researchers) through an on-going understanding of the joint problem space as a network of meaningful reference. For Team B, the VMT whiteboard makes their joint problem space visible and persistent as it evolves.

Utterance: Recipient design for reading's work

While both the students who participate in the sessions and the researchers who analyze the logs need to understand the network of references, they understand them in very different ways. The students understand how to respond to what is going on the way they might know how to ride a bike. That is, they are not reasoning about it explicitly, rationally, logically, consciously. Rather, they are paying attention to what is going on and responding knowingly and intuitively. Quicksilver has not carried out any kind of analysis of Aznx' word "it" the way I did; yet he could respond to it with a sophisticated set of questions. He only had a couple of seconds to respond, whereas I, as a researcher, could spend hours going back and forth over the log reasoning about explicit interpretations.

People are incredibly skilled at using language without thinking about how they do it. In fact, even researchers are only aware of a small percentage of what people take into account almost instantaneously without being aware of it. We say that Aznx "designs" his announcement and proposal so that it will be read by Bwang and Quicksilver in a way that will lead them to understand in a complex way. They will figure out what "it" is referencing, but also realize some of the ambiguity of the reference. They will also come to think about the strategy for finding the number of squares in the diamond pattern because of this ambiguity. However, Aznx does not design his statement explicitly, through a rational sequence of logical arguments. Rather, as a skilled user of language, he gives voice to a well-designed posting that responds to the current discourse situation. It is somewhat like the way a skilled off-road biker responds to the terrain intuitively as she is speeding down a rough hillside with no time to think about what she is doing—and she somehow designs an optimal path for her journey.

Aznx was successful in designing his question so that it would be read in a certain way within the context of the group's discussion in their joint problem space. This is what ethnomethodology calls the "accountability" of utterances (Garfinkel, 1967). This simply means that utterances are designed to be understood by their recipients, by the audience for whom they are intended. That is, utterances are designed to meet the expectations of their recipients (Garfinkel, 1967). They include an "account" of how they should be read, embedded in the design of their presentation. In chat, postings are designed to be read in a certain way by the other chat readers. We call this "recipient design." This is analogous to utterances in spoken talk, which are designed to be heard, and are therefore given subtle vocal emphasis and timing. Chat postings, on the other hand, can incorporate capitalization, abbreviations, symbols, punctuation, emoticons and special fonts. They can reference previous postings that occurred further back in time because the chat text is persistent, remaining visible or retrievable for longer than speech. In chat, group work takes place as reading; chat postings must be designed to support reading's work of understanding the posted utterances in their discourse context (Livingston, 1995; Zemel & Çakir, 2009).

Response pair: Projection and uptake

An important aspect of the design of utterances or postings is how they are designed to fit into what comes before and after them. In general, an utterance performs an uptake or response to something that came before (Suthers, Dwyer, Medina & Vatrapu, 2010a). At the same time, it elicits a follow-up, or at least makes relevant certain forms of subsequent utterances by others (Schegloff, 2007). Through its uptake and projection, an utterance provides continuity to the discourse—in fact, it thereby creates a temporal structure (Heidegger, 1927/1996).

The clearest and simplest example of this is the adjacency pair or response pair, such as a question/answer pair. A question elicits an answer. That is, stating a question projects that an answer will be given in response. It opens a conversational space for an answer. It makes it relevant for the next utterance to be an answer responding to the question. In other words, a question is designed to be read as something that should be responded to with an answer. A question worded like "Can you see how it fits inside a square?" is designed to be answered with a "yes" or a "no." The question-and-answer pair forms a unity, a small unit of interaction between people. The "yes" response shows that the posting it is responding to was read as a question and creates the pair as a successful question/answer interaction.

One of my first discoveries in studying virtual math teams was that math discourse is largely driven forward by what I called "math proposal response pairs" (Stahl, 2006a; 2006b). These have the following structure:

An individual makes a bid for a proposal to the group suggesting how the group should continue to do its mathematical work.

Another member of the group accepts (or rejects) the proposal on behalf of the group.

This is the simple, default form of the math-proposal response pair. If the proposal is accepted, then work begins on the proposal, often in the form of a follow-up proposal.

Of course, there are many variations and complications possible. The bid can be ignored or never responded to. In that case, it does not function as an effective proposal; at best it is a "failed proposal." Before a proposal response is made, there can be other response pairs inserted in the middle of the expected pair—such as a clarification question. It is also possible that someone will propose an amendment to the proposal bid before the original is accepted. Thus, a simple pair can develop a complicated recursive structure of insertions, extensions, repairs, etc.—with each of these being subject to their own insertions, extensions or repairs. Eventually, each of the intervening pairs may get closed with its anticipated response and then the original pair may be completed.

Move: Getting the problem-solving work done

Group problem-solving moves often have the structure of a longer sequence than a simple pair. Such a longer sequence may consist of a complex of response pairs embedded in one another. To identify such a structure, it may be necessary to first conduct a threading analysis to determine what is responding primarily to what. Then, it is often useful to see how this longer response sequence is built up out of simple response pairs (Stahl, 2011).

Together, these intertwining response pairs form a successful move, introducing a new theme for the group. As an example, let's look again at Aznx's move in Figure 9.

line	start	post		
919	19:35:26	19:35:36	Aznx	I have an interesting way to look at this problem.
920	19:35:41	19:35:42	Quicksilver	Tell us
921	19:35:38	19:35:45	Aznx	Can you see how it fits inside a quare?
922	19:35:45	19:35:45	Bwang	yes
	19:35:49	19:35:52	Bwang	[user erased message]
923	19:35:51	19:35:52	Quicksilver	Yes
924	19:35:52	19:35:53	Bwang	oh
925	19:35:55	19:35:55	Bwang	yes
926	19:35:53	19:36:01	Quicksilver	You are saying the extra spaces...
927	19:35:58	19:36:05	Aznx	Also, do you see if you add up the missing areas

Figure 9. The move to introduce Aznx' new way of looking at the group's problem.

We can see four response pairs there:

- Aznx announces, "I have an interesting way to look at this problem" and Quicksilver responds by asking him to "Tell us."
- Aznx asks, "Can you see how it fits inside a square?" and first Bwang responds "yes." Then Quicksilver responds, "Yes." Then Bwang responds again, more emphatically, "oh … yes."
- Quicksilver asks a clarification question about the proposal implicit in Aznx' question, "You are saying the extra spaces …[?]"

- Aznx, in parallel with Quicksilver's question asks a follow-up question, which contains an implicit further proposal about the group's work: "Also, do you see if you add up the missing areas [...?]"

As the discussion continues, Quicksilver responds to Aznx' question and the two of them continue to discuss the issues raised in both their questions.

Theme: Coherent interactional sequence

Aznx' *move* introduces the *theme* of the diagonal pattern viewed as enclosed in a square with missing spaces in the four corners. As we have just seen, the move consists of multiple response pairs that drive the work of the group to consider this theme.

As the theme evolves, the group draws and discusses some increasingly elaborate drawings to view the patterns that the theme involves. The group considers different stages of the pattern (N=1, 2, 3, 4) and how the number of missing spaces changes as the diamond pattern grows.

This leads them right to the point where they can formulate an equation to summarize their analysis of the pattern growth. Unfortunately, Bwang has to leave the session and they do not complete this work. During the fourth session two days later, the group picks up this theme and discusses it repeatedly, eventually deriving the equations for number of squares and sticks in the diamond pattern at all stages (Stahl, 2011). This theme is the basis for the equation for number of squares, which simply subtracts the number of missing spaces in the four corners of a square that encloses the diamond pattern.

Session: temporal structuring and re-member-ing

After Bwang left the third session, Aznx and Quicksilver try to review the group's accomplishments. They become confused about various equations and unsure of their ability to explain what the group has figured out. They end the session with Quicksilver saying, "then let's pick it up next time when Bwang can explain it." This ends one session and projects what will happen in a future session.

When the group meets for the fourth session, Aznx and Quicksilver do eventually get Bwang to review the derivation of the equation based on the view of the problem that Aznx introduced in the theme we just considered. The discussion in session four refers back to the group's work in session three and also to Team C's work in session two. But it does this in ways that are situated in Team B's session-four context (Sarmiento-Klapper, 2009). The team members and the memories they bring with them from the past are re-constituted in the new situation, made relevant to the current themes, problem space and available resources. The group remembering process makes the individual students who are present in the new sessions members of the group: it is a re-member-ing process, necessary at the start of many sessions, especially where the group membership has changed.

Event: Forming groups and co-constructing knowledge artifacts

At the beginning of session one, the students were not part of a particularly effective group or team. They did not build much on each other's contributions and were hesitant to make proposals, ask each other to undertake tasks, produce permanent drawings or manipulate mathematical symbols. That all changed dramatically during their four-session event. By the end, they had many graphical, narrative and symbolic representations or expressions related to their mathematical topic. They worked effectively together and solved their problems well. Problem-solving methods that one person introduced were later proposed and used by the other group members. Effective collaboration comes with interaction practice.

You may be wondering if each of the students learned mathematics. The interesting thing about looking closely at what really went on in this event is that what we traditionally consider to be the math content actually plays a relatively minor role in the group's problem solving. Yes, content is brought in: the students talk about triangular numbers, and they apply the formula for summing consecutive integers, for instance. Often, this math content is brought in quickly through proposals by individuals. It is then discussed through responses to the proposal that check that everyone understands the math content and agrees on its applicability. However, the bulk of the hard work is not accessing the traditional math content, but selecting, adapting, integrating, visualizing, sharing, explaining, testing, refining, building on and summarizing sequences of group response pairs. These proposals and discussions reference not only math content, but also various related resources that the group has co-constructed.

The learning and thinking of the group take place through the group's discourse, as a temporally unfolding multi-level structure of response pairs interwoven into larger sequences of group moves, problem-solving themes, and sessions of events. The group learns about the mathematics of its topic by building and exploring an increasingly rich joint problem space. It thinks about the mathematical relationships and patterns by following sequences of proposals, raising and responding to various kinds of questions, and engaging in other sorts of interactional moves. Some of this gets summarized in persistent knowledge artifacts like drawings, concepts, equations, solution statements and textual arguments. The building of the joint problem space generally requires a lot of work to resolve references and to co-construct a shared network of meaning (Stahl, Zhou, Çakir & Sarmiento-Klapper, 2011).

The math skills—like following certain procedures to do long division or to transform symbols—are not where the deep learning takes place and real knowledge is involved. Rather, the ability to sustain progressive inquiry through methods of group interaction is the real goal. This ability makes use of the math skills as resources for answering questions and coming up with new proposals.

If you wonder how to view learning and thinking in CSCL groups, follow Wittgenstein's advice: "Don't think, look!" My colleagues and I have tried to do this by looking at the work of virtual math teams in the way I have just described. We have been amazed to discover that collaborative learning and group cognition are a lot different than people thought.

CSCL as a New Approach to Computers in Education

Reading is learning, but applying is also learning
and the more important kind of learning at that….
It is often not a matter of first learning and then doing,
but of doing and then learning, for doing is itself learning.

--Chairman Mao 毛泽东 (1936)

Computers in education bring many advantages, even as seen within a traditional view of education:

- They give students and teachers access to all the information on the Web.
- They provide the ability to access lectures anywhere/anytime/on large scales.
- They can support testing, tutoring and scripting of learning processes.
- They offer simulations, educational gaming, virtual reality and artificial intelligence.

But networked computers in education—using CSCL software environments like VMT—also open opportunities for a radically new view of learning and thinking:

- Networking of students can let them get together with others interested in similar topics around the world.
- Effective collaborative-learning experiences help students learn how to work, think and learn in groups. Group work is a new force of production in the world, and students need to learn how to produce knowledge in teams.
- CSCL events can give students first-hand, hands-on experience in knowledge building.
- Discussing mathematics in peer groups teaches students how to do math, how to talk about math, how to make math connections, how to learn math and how to think mathematically.

In this second view of computers in education, book learning of facts and rote procedures has a place, but the more important kind of learning comes through doing. CSCL groups can provide effective learning experiences in which teams of students actually do mathematics by exploring rich problem spaces and discussing them—the way that Aznx, Quicksilver and Bwang did.

There are *two* popular approaches to CSCL theory:

- Collaborative learning can be seen as an *extension* of traditional *individual* learning. Individuals possess knowledge that they can state in sentences and can communicate to other individuals. Our commonsense concepts can describe this, and we can measure what individuals know at different times. Learning in this traditional view is an increase in individual knowledge
- Collaborative learning can be viewed as being *qualitatively* different from traditional individual learning, and we need to *discover* the nature of collaborative learning and its relation to individual learning by exploratory research. We need to *re-think* our ideas about learning, collaboration, education, computer support, research methodology and cognitive theory (Stahl, 2006a). We need to look carefully at data from real CSCL sessions to see what *actually* takes place there, without imposing our commonsense views.

It should be clear by now that *I view* learning and thinking in CSCL groups as a mystery to be investigated, not as something well understood to be measured. It is a new form of human existence with great potential. We must observe it to learn how it works. My colleagues and I have begun to do this, as have other researchers in CSCL. I have tried to indicate to you here how you can go about observing learning and thinking in CSCL groups.

It may be easier to understand issues of technology design and of traditional instruction when studying computers in education than to understand this new view of learning and thinking. However, I believe that if we hope to get the most benefit from computers in education and to understand how groups learn and think in CSCL groups, then we will have to closely observe the discourse and interaction in ways similar to what I have presented here.

Afterword: Notes on Group Cognition

When one studies logs of virtual math teams, one sees that the teams spend a lot of time and effort constructing *shared understanding* about references in their postings. The reason that teams and other small groups devote so much time and energy to resolving confusing references is that the network of references that they build up together plays an essential role in their group learning and thinking. In the theory of CSCL, there is considerable emphasis on the idea of "common ground" (Clark & Brennan, 1991) and "joint problem space" (Teasley & Roschelle, 1993). A group establishes common ground largely by reaching a shared understanding of how references work in their discourse. As it interacts over time, a group co-constructs a network of references that can become quite complex.

The "shared understanding" that is built up is akin to the notion of *co-orientation*, which refers to the mutual orientation of individuals in a group toward an object (knowledge, belief, attitude), and can be traced back to the interactionist social psychology of John Dewey and George Herbert Mead. Psycho-linguistic metaphors of comparing stored mental representations are unnecessary and can be misleading, reducing all knowledge to individual mental possessions. Team members share a world centered on their task; they orient as a group to the objects that populate that world, such as Aznx' proposals, Bwang's drawings and Quicksilver's queries. *Because they share a common world*—which they co-constitute largely through their discourse, mediated by the larger common social, cultural and historical horizons of their world—*they can co-construct a shared understanding*.

The shared network of references defines the context or *situation* in which the group discourse continues to take place (Heidegger, 1927/1996, §18). Aznx' reference to "it" that we looked at contributed to a network of meaning that the group built up continuously through their interaction. This network included images of sticks in various patterns (like diamonds at stage N=2 and N=3), the relationships of the patterns (like a diamond enclosed in a square with stair-step empty corners), concepts referred to by technical terms (like "triangular numbers" or "summation") and symbols representing mathematical operations (like equations for number of squares in a pattern).

The co-construction of shared understanding by a small group is what I refer to as "group cognition."

This Investigation represents a disciplinary perspective from Computer-Supported Collaborative Learning (CSCL), an interdisciplinary field concerned with leveraging technology for education and with analyzing cognitive processes like learning and meaning making in small groups of students (Stahl et al., 2006). *Group cognition* is a theory developed to support CSCL research by describing how collaborative groups of students could achieve cognitive accomplishments together and how that could benefit the individual learning of the participants (Stahl, 2006a).

It may well be that a group of students working together manages to solve problems faster than any of the individual students may have been able to do alone—particularly when the problem is challenging for them. However, the most important benefits of group cognition are the potential for genuinely innovative solutions that go beyond the expertise of any individual in the group. It is the deeper understanding that is achieved through the interaction as part of that creative process—and the lasting impact of that deep understanding that the students take with them when they move on from that interaction—which they may then carry with them as new resources into subsequent group problem-solving scenarios. Group cognition can then be seen as what transforms groups into factories for the creation of new knowledge.

The types of problems that have been the focus of exploration within the group-cognition paradigm have not been routine, well-structured problems where every participant can know exactly what their piece of the puzzle is up-front in such a way that the team can divide up the work, *cooperate* and function as a well-oiled machine. Many critical group tasks do not fit into well-known and practiced protocols—for example, low-resource circumstances that may occur in disaster situations, where standard solutions are not an option. In acknowledgement of this, the focus within the group-cognition research has been on problems that offer groups the opportunity to explore creatively how those problems can be approached from a variety of perspectives, where the groups are encouraged to *collaborate* and explore unique perspectives.

The processes that are the concern of group-cognition research have not primarily been those that are related to efficiency of problem solving. Rather, the focus has been on the pivotal moments where a creative spark or a process of collaborative knowledge building occurs through interaction. Our fascination has been with identifying the conditions under which these moments of group inspiration are triggered, with the goal of facilitating this process of team innovation and collaborative knowledge creation.

The field of CSCL has explored what makes group discussions productive for learning under different names, such as *transactivity* (Berkowitz & Gibbs, 1983; Teasley, 1997; Azmitia & Montgomery, 1993; di Lisi & Golbeck, 1999), *uptake* (Suthers, 2006), *social modes of co-construction* (Weinberger & Fischer, 2006), or *productive agency* (Schwartz, 1998). Despite differences in orientation between the subcommunities where these frameworks have originated, the conversational behaviors that have been identified as valuable are quite similar. Specifically, these different frameworks universally value explicit articulation of reasoning and making connections between instances of articulated reasoning. For example, Schwartz and colleagues (1998) and de Lisi and Golbeck (1999) make very similar arguments for the significance of these behaviors from the Vygotskian and Piagetian theoretical frameworks, respectively. The idea of transactivity as a property of a conversational contribution originates from a Piagetian framework and requires that a contribution contain an explicit reasoning display and encode an acknowledgement of a previous explicit reasoning display. However, note that when Schwartz describes from a Vygotskian framework the kind of mental scaffolding that collaborating peers offer one another, he describes it in terms of one student using words that serve as a starting place for the other student's reasoning and construction of knowledge. This implies explicit displays of reasoning, so that the reasoning can be known by the partner and then built upon by that partner. Thus, the process is very similar to what we describe for the production of transactive contributions. In both cases, a transactive analysis would say that mental models are articulated, shared, mutually examined and potentially integrated.

Group cognition is a post-cognitive theory [Investigation 15]. Post-cognitivism is a tradition characterized by situated, non-dualistic, practice-based approaches. Cognitivism—which retains theoretical remnants of the Cartesian dualism of the mental and physical worlds—originally arose through the critique of behaviorism, with the argument that human responses to stimulae in the world are mediated by cognitive activity in the mind of the human agent. This argument was particularly strong in considerations of linguistic behavior (Chomsky, 1959). More recently, post-cognitivist theories have argued that cognitive activity can span multiple people (as well as artifacts), such as when knowledge develops through a sequence of utterances by different people and the emergent knowledge cannot be attributed to any one person or assumed to be an expression of any individual's prior mental representations (e.g., Bereiter, 2002, p. 283).

Group-cognition theory explicitly focuses on these inter-personal phenomena and investigates data in which one can observe the development of cognitive achievements in the interactions of small groups of people, often in online collaborative settings, where interactions can be automatically logged. By interaction, we mean the discourse that takes place in the group. Group cognition is fundamentally a linguistic (speech or text) process, rather than a psychological (mental) one. Thus, unlike the theory of transactivity described above, this post-cognitive approach does not assume cognitive constructs such as mental models, internal representations or retrievable stores of personal knowledge. In the online setting of VMT, cognition is analyzed by looking closely at the ways in which meaning is built up through the interplay of text postings, graphical constructions and algebraic formulations (Çakir, Zemel, et al., 2009) [Investigation 12].

There is a tension between the human sciences and the natural sciences, between *understanding* team cognition (e.g., with micro-analysis of situated case studies) and *explaining* it (e.g., modeling, confirming general hypotheses, formulating laws and specifying predictive causal relations). Group cognition in online teams involves both humans and computers—both highly situated collaborative interactions and programmed computer support. Thus, the analysis of group cognition must integrate the identification of characteristic patterns with the recognition of irreducible uniqueness of cases.

In our research, our colleagues and we look at logs of student groups chatting and drawing about mathematics in order to see if they build on each other's ideas to achieve more than they would individually. How do they understand each other and build shared language and a joint problem focus? What kinds of problems of understanding do they run into and how do they overcome those? How do they accomplish intersubjective meaning making, interpersonal trains of thought, shared understandings of diagrams, joint problem conceptualizations, common references, coordination of problem-solving efforts; planning, deducing, designing, describing; problem solving, explaining, defining, generalizing, representing, remembering and reflecting as a group? What can we say about the general methods that small groups use to learn and think as groups? How can we support and encourage this better with software support for social awareness, social networking, simulations, visualizations, communication; with intelligent software agents; with pedagogical scaffolds and guidance; with training and mentoring; with access to digital resources; with new theories of learning and thinking? To answer these complex questions, we must look carefully at the details of discourse in CSCL groups and develop innovative tools (both analytic and automated) and theories (of cognition by individuals, small groups and discourse communities).

The field of CSCL is particularly interested in the ways small groups can build knowledge together thanks to communication and support from networking technology. We hope that CSCL environments can be designed that make possible and encourage groups to think and learn collaboratively.

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Notes