Advancing a CSCL Vision

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Abstract. The field of computer-supported collaborative learning (CSCL)—as a unity of educational practice and academic research—is characterized in this Investigation by a specific vision of 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 of these endeavors 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, 2016) is carried out at the small-group unit, documenting how the team adopted over 60 "group practices" [Investigation 16] 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.

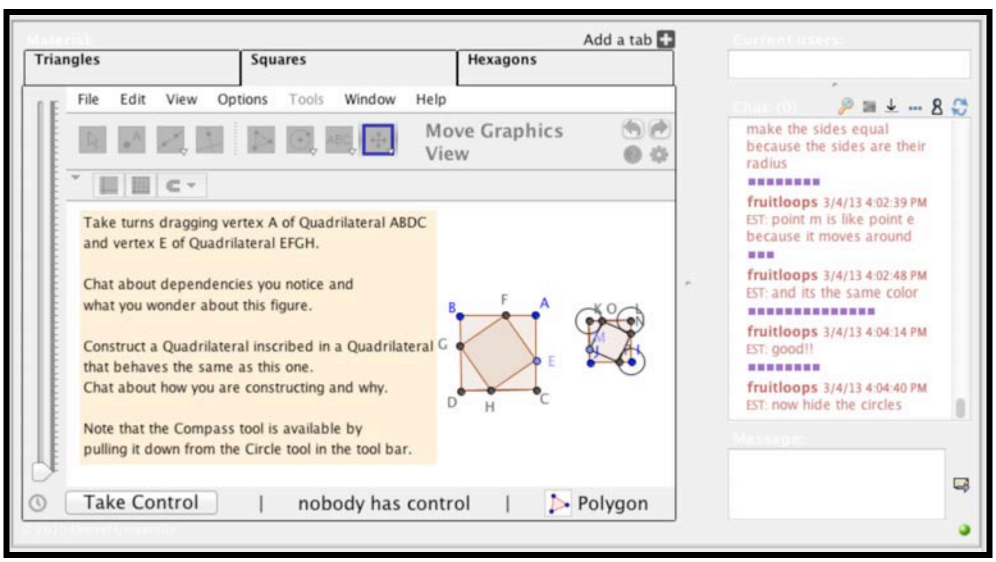

Figure 1. The VMT interface. The team has constructed square IJKL and inscribed another square inside it, based on exploration of the given example of square ABCD and past group experience constructing inscribed triangles.

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 in this tradition 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 (group) meaning making within these settings, rather than in traditionally conceived (individual) 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 are 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 Investigation 3 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 [Investigation 15], 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. Investigation 3'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.

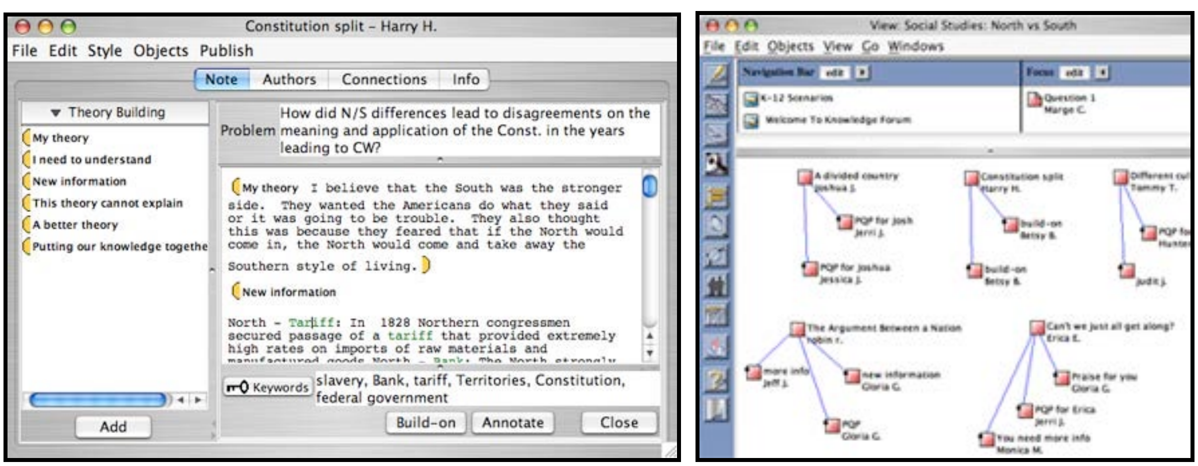

Figure 2. Knowledge Forum interface. Students enter theory-building notes (left). A view of interrelated notes is displayed graphically (right).

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, Amazon, Apple, Microsoft 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.

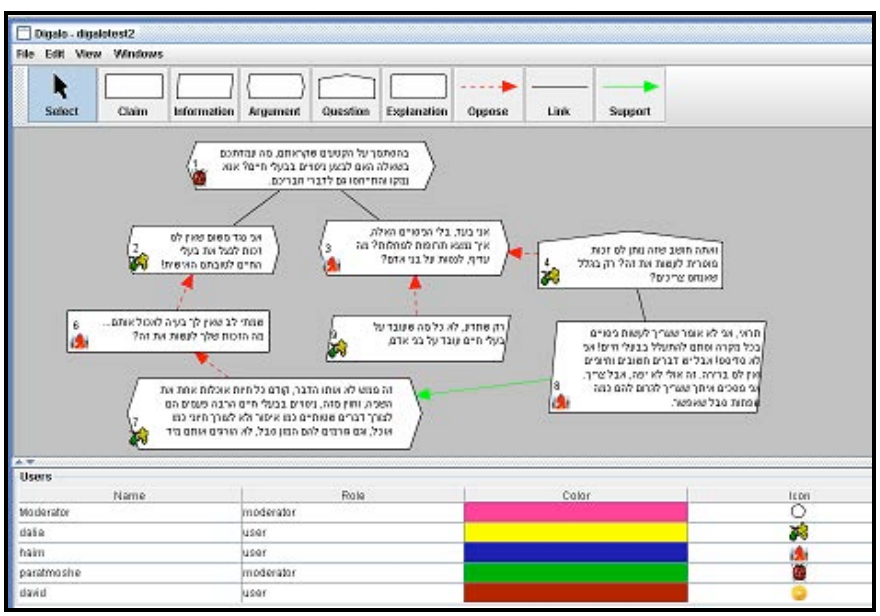

Figure 3. The Digalo interface. Students contribute elements of an argument and represent their role in the overall structure of the argument.

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)).

Investigation 5 details the work of problem solving as involving referential practices. Zemel & Koschmann show 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. (The building of representations and the identification of indexical properties—which take time or effort and distract from immediate accomplishments—may explain the intriguing paradox of "productive failure" in CSCL groups (Kapur & Kinzer, 2009). 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)** [Investigation 6]. 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, make sketches, record information, talk things out. 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 assessing 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 facts, 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 facilitation 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:

a) The new CSCL tool led to more learning;

b) The tool worked as designed; and

c) Collaborative learning is effective.

Rather, the theory suggests, for instance, that:

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

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

c) 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:

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

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

c) 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 [Investigation 25].

Sfard's book was reviewed in *ijCSCL* by (**Stahl, 2008)** [Investigation 8]. Sfard 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. Öner's study investigates two routines:

1. The production of the perpendicular: This routine was gradually altered from drawing by visual placement to construction by creating dynamic-geometry dependencies.
2. 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 student team's notion of perpendicular referred to a visual image. It gradually evolved toward 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 individuals.

The way that actions and conceptualizations shifted in starts and fits 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 socio-cultural 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 who 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 effort 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. This is a nice example of the use of graphical inscription to take advantage of visual skills.

A student constructed the whiteboard diagram of the stack of blocks at the bottom of 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.

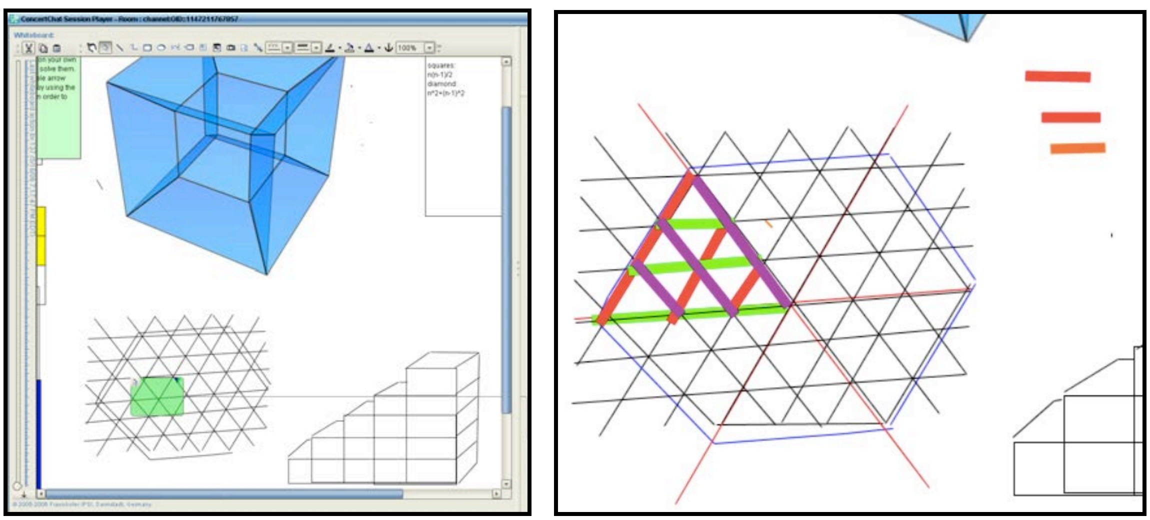

Figure 4. The VMT interface with a student construction of a hexagon array and of stacked blocks (left). Colored lines decompose a large hexagon into sequences of small triangles (right).

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 (e.g., graphical, representational, symbolic, spatial, highlighted, color-coded, labeled, etc.).

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 that 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). This analysis 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 analyzed 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 presumed mental re-presentations of them. The understanding of the references is a matter of normally tacit social practices, rather than of rationalist explicit deduction [Investigation 15].

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 Gauss' 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 in the interface. Both of these practices were adopted by the team, then understood and used repeatedly by all team members as "group practices" [Investigation 16] 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:

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

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

c) The team's adoption of group practices—which may indirectly 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 and technological support are recommended to illustrate inventive ways to extend the CSCL paradigm. Although they could not be included in this already thick volume, they are available in back issues of *ijCSCL*:

1. **Schneider and Pea (2013)** 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 see 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.
2. **Chen, Scardamalia and Bereiter (2015)** 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 eight years old.
3. **Kapur and Kinzer (2009)** 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 conceptualization, decomposition, representation, inscription or 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 to long-term group learning of temporary failure also problematizes the traditional emphasis on testing the short-term success of individuals.

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 [Investigation 2]. Identifying the adoption of group practices may inform and even guide this analysis.

Design-based research (DBR) is widely recognized in CSCL as a necessary 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 the following, 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 review of two reports in *ijCSCL*.

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 13] 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 and 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 14] 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—(1) context and systemic change, (2) capacity and community building, and (3) 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, to *innovate* themselves. 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 (OECD, 2017) ranked Singapore number one and Hong Kong number three out of 51 tested countries in 2015, a couple years after the interventions reviewed here. 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 the VMT 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. The VMT Project ported the free, open-source GeoGebra software to the VMT multi-user collaboration 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 in to 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 experiences with collaborative learning or with 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 reach 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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