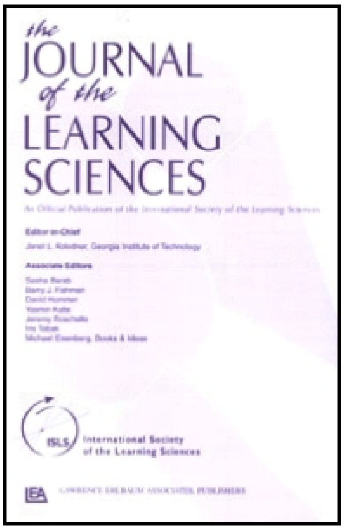

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Designs for Collective Cognitive Responsibility in Knowledge-Building Communities

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Designs for Collective Cognitive Responsibility in Knowledge-Building Communities

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This article reports a design experiment conducted over three successive school years, with the teacher's goal of having his Grade 4 students assume increasing levels of collective responsibility for advancing their knowledge of optics. Classroom practices conducive to sustained knowledge building were co-constructed by the teacher and students, with Knowledge Forum software supporting the production and refinement of the community's knowledge. Social network analysis and qualitative analyses were used to assess online participatory patterns and knowledge advances, focusing on indicators of collective cognitive responsibility. Data indicate increasingly effective procedures, mirrored in students' knowledge advances, corresponding to the following organizations: (a) Year 1—fixed small-groups; (b) Year 2—interacting

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small-groups with substantial cross-group knowledge sharing; and (c) Year 3—opportunistic collaboration, with small teams forming and disbanding under the volition of community members, based on emergent goals. The third-year model maps most directly onto organic and distributed social structures in real-world knowledge-creating organizations and resulted in the highest level of collective cognitive responsibility, knowledge advancement, and dynamic diffusion of information. Pedagogical and technological innovations to enculturate youth into a knowledge-creating culture, with classroom practices to encourage distributed and opportunistic collaboration, are discussed.

There is a growing demand for schools to produce a citizenry with 21st-century capabilities. Among these 21st-century capabilities, the ability to create knowledge is paramount. Knowledge creation has traditionally been framed in terms of individual creativity, but recent literature has placed more emphasis on social dynamics (e.g., J. S. Brown & Duguid, 2000; Csikszentmihalyi, 1999; Sawyer, 2007). Of commonly promoted practices, inquiry-based learning arguably comes closest to supporting the needs of education for a Knowledge Age. Current inquiry-based learning practices often involve fixed small-group collaboration as a design feature (Wells, 2002). Recent literature has suggested that sustained, creative knowledge work can be better supported through distributed, flexible, adaptive, social structures than centralized, rigid, or fixed structures (Amar, 2002; Chatzkel, 2003; Engeström, 2008; Sawyer, 2003; Williams & Yang, 1999). The present design-based research examines the social structures that evolved in a knowledge-building classroom over 3 years—from fixed small groups to interacting groups to flexible, opportunistic collaboration—with the goal of enabling collective responsibility for community knowledge advancement (Scardamalia, 2002).

Knowledge building—the creation of knowledge as a social product—is something that scientists, scholars, and employees of highly innovative companies do for a living (Bereiter, 2002). The work reported here aims to support the claim that such high-level knowledge work can be integral to schooling, starting at least in the middle elementary grades. Support for the broader claim that such work is feasible across a broader range of ages, socioeconomic contexts, teachers, and other factors is not addressed in this article but is part of the work of the international Institute for Knowledge Innovation and Technology (www.IKIT.org).

COLLECTIVE COGNITIVE RESPONSIBILITY FOR COMMUNITY KNOWLEDGE

Having students become active agents in knowledge construction is an important theme in the learning sciences literature (Bell & Linn, 2000; Engle & Conant, 2002; Herrenkohl & Guerra, 1998; Lamon et al., 1996; Lehrer, Carpenter, Schauble,

& Putz, 2000; Paavola & Hakkarainen, 2005; Scardamalia & Bereiter, 1994; Tabak & Baumgartner, 2004). To what extent can students take over goals typically assumed by the teacher? Of particular interest in this regard is *collective cognitive responsibility*, which requires taking responsibility for the state of public knowledge (Scardamalia, 2002). It combines high levels of social as well as cognitive responsibility, engaging students in what knowledge-creating groups do in innovation-generating organizations (Bereiter & Scardamalia, in press). This includes reviewing and understanding the state of knowledge in the broader world, generating and continually working with promising ideas (Bereiter & Scardamalia, 1993), providing and receiving constructive criticism (Sawyer, 2007), sharing and synthesizing multiple perspectives (Bielaczyc & Collins, 2006), anticipating and identifying challenges and solving problems (Leonard-Barton, 1995), and collectively defining knowledge goals as emergents of the process in which the group members are engaged (Sawyer, 2003; Valsiner & Veer, 2000). Members take responsibility for sustained, collaborative knowledge advancement, collaborative learning, as well as personal growth. They connect their own interests and expertise with those of the community to achieve their individual and collective goals (Amar, 2002).

To take over high levels of social and cognitive responsibility, students must recognize that their own ideas, like ideas in general, can be continually improved. They do this by working toward deeper explanations and higher level conceptualization that gives them greater explanatory power (Thagard, 1992). Additionally, student ideas must have an "out-in-the-world" existence (Bereiter, 2002; Scardamalia, et al., 1989). They are not equivalent to personal knowledge or beliefs; rather, theories, inventions, models, plans—the intellectual life of the community—are accessible as knowledge objects to all. In the business world, this is referred to as the organization's *corporate knowledge*; in the knowledge-building literature, we refer to it as *community knowledge* (Scardamalia, 2002; Scardamalia & Bereiter, 2006). This community knowledge space is typically absent from classrooms, making it hard for students' ideas to be objectified, shared, examined, improved, synthesized, and used as "thinking devices" (Wertsch, 1998) to enable further advances. To address this challenge, our research team developed the Computer-Supported Intentional Learning Environment (CSILE); Scardamalia, et al. (1989) and its upgraded version, Knowledge Forum® (see Scardamalia, 2004, for details). The heart of CSILE/Knowledge Forum is a networked, communal knowledge space. By authoring or coauthoring *notes* that may include multimedia elements, students contribute ideas, models, problems, plans, data, and so on to their shared space. At a higher level of organization, they create graphic *views* as workspaces for different inquiry goals, to organize their ideas represented in notes. To promote effective knowledge work in this community space, Knowledge Forum provides supportive features that allow users to *build on*, make *annotations*, add *reference* links to one another's notes, and create *rise-above* notes and views to summarize, distill, and advance their understanding and create higher order integrations of ideas. *Scaffolds* help them engage in high-level cognitive operations: theory improvement; creation of working models and plans; presentation of evidence, data, and reference material; and so forth. Having this community knowledge space and its related interaction tools helps to enable collective responsibility for knowledge advancement.

Collective cognitive responsibility is important in today's knowledge-based organizations (Nonaka & Takeuchi, 1995). An interesting example is the design of the Boeing 787 aircraft, built by nearly 5,000 engineers (excluding production workers) around the world. The design and engineering work took place simultaneously at multiple sites, over a long period of time, and yet all of the parts fit nicely together (Gates, 2005). In a collaborative, creative endeavor of this nature, team members need to understand the top-level goal and share responsibility for the interrelated network of ideas, subgoals, and designs, with success dependent on all members rather than concentrated in the leader. Members share responsibility for establishing effective procedures, for assigning and completing practical tasks, for understanding and facilitating team dynamics (Gloor, 2006), for remaining cognitively on top of activities and ideas as they unfold (Leonard-Barton, 1995; Scardamalia, 2002), managing the process as a whole. As issues emerge, they collectively shape next steps, build on one another's strengths, and improve their ideas and designs. Their ability to "rise above" current understandings to a higher plane is reflected in their ability to work at the cutting edge of their understanding (van Aalst & Chan, 2007). Members create the cultural capital of their organization as they refine the "knowledge space" and products that represent their collective work. Of course this work includes timelines, specified goals, and deadlines. The idea of collective responsibility is not to ignore such aspects but to engage participants in setting deadlines, taking responsibility for achieving them, and redefining goals and schedules as necessary.

In order to inform and examine designs for collective cognitive responsibility in knowledge-building communities, we attempt to unpack related concepts and provide operational definitions of several facets, with reference from the learning sciences and knowledge management and innovation literature.

Awareness of Contributions

Collective cognitive responsibility requires knowing the players in the game (Orlikowski, 2002) and understanding the changing goals, situations, actions, and connections in a community (Weick & Roberts, 1993). To advance knowledge in a dynamic community, team members need to deal with emergent problems and goals as the agenda evolves and participant contributions alter the problem space. As a social norm, members need to understand and monitor advances throughout that community space and consult others' work when contributing their understandings, instead of ignoring the relevant work of others (Engle & Conant, 2002; Palincsar, Anderson, & David, 1993; Resnick & Hall, 2001).

Complementary Contributions

Collective cognitive responsibility also requires that members advance the joint enterprise, in the context of joint activity (Koschmann, 2002). Mutual engagement thus "involves not only our competence, but also the competence of others. It draws on what we do and what we know, as well as on our ability to connect meaningfully … to the contributions and knowledge of others" (Wenger, 1998, p. 76). Members in a knowledge-building community must accordingly make complementary contributions. It is important to respond to and build on one another's ideas (Palincsar et al., 1993) and contribute nonredundant and important information that advances the enterprise as a whole. This is the antithesis of much schoolwork in which students are all doing the same thing, with no idea diversity to drive the need for explanatory coherence. In knowledge building, by contrast, students build on one another's idea contributions and then rise above to find increasingly high-level accounts, helping to create the coherence that drives them toward deeper understanding.

Distributed Engagement

Collective responsibility goes beyond awareness and complementarity of contributions; it additionally requires that participants engage in top-level planning, decision making, and community coordination, as opposed to having the highest level executive processes rest with "the leader." It thus requires a distributed rather than centralized framework for these high-level operations with minimal hierarchical control (De Leede, Nijhof, & Fisscher, 1999; Weick & Roberts, 1993). To foster collective cognitive responsibility in classroom, the teacher needs to adjust his or her role to include more symmetry in classroom interactions (Tabak & Baumgartner, 2004), empowering students to work with goals that emerge from their interactions and correspondingly to initiate new, extended lines of discourse instead of only responding to questions and tasks generated by their teacher (Lemke, 1990). Students, like their teacher, have equal opportunities to contribute to the flow of the interaction (Cazden, 2001). Thus, they must elaborate goals and monitor gaps, weaknesses, and conflicts in their community knowledge, noting the extent to which they are meeting goals or falling short, and adjusting their courses of action and social organization. In contrast, inquiry-based learning models, especially for lower grade levels, tend to leave top-level decisions (i.e., defining inquiry goals, division of labor, scheduling) with the teacher (Chinn & Malhotra, 2002).

SOCIAL CONFIGURATIONS CONDUCIVE TO COLLECTIVE COGNITIVE RESPONSIBILITY FOR COMMUNITY KNOWLEDGE

To enable collective cognitive responsibility for community knowledge among young students, this research examines different design frameworks that vary along the dimension of fixed, imposed structure versus flexible, emergent structure. These frameworks can be characterized as follows: (a) *fixed groups*, in which collaboration takes place in fixed small groups, with different groups focusing on different aspects of the inquiry and coming together at the end to combine their work; (b) *interacting groups*, an enhanced version of small-group collaboration with more cross-group knowledge sharing and interactions throughout the process; and (c) *opportunistic collaboration*, in which groups form, break up, and recombine as part of an emerging process, with all participants aware of and helping to advance the structure of the whole.

Currently, small-group collaboration represents a dominant design feature for student collaborative work within communities of learners and inquiry learning contexts in both face-to-face and online environments. In these contexts, groups are often fixed for the duration of the inquiry; some models accommodate rotations and other means of distributing the knowledge gained by different teams as they work toward some culminating task or artifact. This small-group design has been regarded as the principal way of breaking the "one-to-many" pattern of teacher-mediated communication and transferring more responsibility to students. However, in order to make the group work manageable and to bring it to conclusion within the predetermined time frame, the teacher often needs to assign definite, time-limited tasks. An inquiry project is designed with different responsibilities for different components assigned to different teams (or different individual members of the team). This "division of labor" or "division of responsibility" makes it less likely that students will assume collective responsibility for achieving top-level community goals; instead, the challenge becomes one of ensuring that all of the work that individual students or small teams have done separately is assembled in the end. This often necessitates a prespecified culminating task and a fixed stage model of inquiry with a timeline for each stage, making clear who will do what, in which format, and by when (Davis, 1993). Inquiry itself is often defined as a process with definable, temporally ordered steps: identify a topic, develop research questions and a plan (often a timetable for answering the question), gather and evaluate data, and make a presentation. Correspondingly, in research of computer-supported collaborative learning, a current focus has been on the design of collaboration scripts—a set of instructions regarding which activities and tasks should be carried out in which sequence, how small groups should be formed, how they should collaborate to finish assigned tasks (see Dillenbourg, 2002, for a critical review). In setting out such plans, the teacher and designer retains most of the high-level cognitive responsibility (see also Chinn & Malhotra, 2002). Although teachers are encouraged to take students' interests and capabilities into account when organizing small groups, once such groups are formed, students tend to remain in that group, with cross-group interactions confined to the final phase in which each group presents its work to other groups. Sometimes, authors of these sequential approaches recognize the need for a more fluid process (Reiser et al., 2001); they recommend these simplified approaches take into account the "realities" of schooling. One of these realities, it is often argued, is that teachers and students are not able to accommodate processes more in keeping with real-world knowledge-creating organizations.

The need to go beyond the fixed small-group approach and encourage cross-group interactions has been discussed by several researchers. Wells (2002) stressed that small-group work is not the only participant structure for a community of inquiry; whole-class participant structures are equally appropriate and indeed necessary at times. Roth and Bowen's (1995) analysis of an open inquiry classroom suggests that knowledge constructed by small groups can be better diffused at the classroom level by increasing cross-group interactions and using whole-class discussions, although in their study small groups were also fixed for the duration of the inquiry. An interesting case was observed in a Fostering Communities of Learners classroom where students requested more time to engage in conversations with members in other groups. This led to the use of a new form of knowledge sharing known as *crosstalk* to support greater interaction between groups in a jigsaw pattern (A. L. Brown & Campione, 1996). But the jigsaw brings its own level of "fixedness." Cross-group exchanges usually take place in fixed phases according to the time scheme and areas of specialization designated by the teacher, so everyone can "rotate" at the same time.

The present study explores new possibilities for engaging dynamic, opportunistic, community-wide collaboration among young students in line with the current view of knowledge creation as a social and emergent process (Sawyer, 2003, 2007; Valsiner & Veer, 2000). Using Sawyer's (2003) term, the social process of knowledge creation is analogous to *collaborative improvisation* without a script; or it is like a daily chat among a group of people without a predecided focus, timeline, or system for conversational turns. Creativity emerges from an interactional process that "involves a social group of individuals engaged in complex, unpredictable interactions" (Sawyer, 2003, p. 19). In this process, diverse ideas are generated, critically examined, and selectively incorporated into emerging complexes.

Coinciding with this emergent perspective, recent literature on knowledge innovation has highlighted the need for knowledge organizations to develop an organic, flat structure that encourages a high degree of adaptability, distributed control, and emergent collaboration (Amar, 2002; Gloor, 2006). These knowledge organizations differ from traditional operating organizations (e.g., factories) that usually have a mechanistic structure based on stable conditions, well-defined tasks and clear division of labor, bureaucratic management, and authority-focused relationships (Williams & Yang, 1999). As Chatzkel (2003) asserted, a knowledge organization "needs to nurture its people so that they feel free to move about in their organization, to group and regroup in different configurations as needed, and to rework themselves and their resources in concert with their new conditions" (p. 20). Members in such knowledge organizations still often work in small groups focusing on certain aspects of their mission, but these groups interact intensively through all kinds of communication and representation tools and form and reform in flexible ways as their situation and specific goals are redefined through their interaction (Cusumano, 2001). They

> work together in a structure that enables a fluid creation and exchange of ideas. Looked at from the outside, the structure … may appear chaotic … but it is immensely productive because each team member knows intuitively what he or she needs to do. (Gloor, 2006, p. 11)

An organic, flexible, and distributed social structure favors an emergent social process of knowledge creation in that it encourages members to collectively define goals as emergents of the communicative process in which they are engaged (Valsiner & Veer, 2000) and to redefine and participate in community practices to achieve their goals, with no participant solely setting the agenda (Barab et al., 1999). As well, people move from group to group and carry their ideas with them, leading to the spread of diverse ideas throughout the community. Dynamic idea spread (knowledge diffusion) is critical to the creativeness of a community (Bielaczyc & Collins, 2006).

This review of the literature elaborates a continuum of frameworks to engage collaborative knowledge work: fixed groups, interacting groups, and opportunistic collaboration. The first approach represents the "standard design" for many inquiry-based classrooms, although the need for enhancing cross-group interaction has been increasingly recognized. Recent theoretical discussions on the emergent process of knowledge creation enlighten the importance and possibility of improvised, opportunistic collaboration in line with a real-world model of knowledge work. However, without detailed empirical studies, this possibility remains vague and controversial (Sawyer, 2004).

THIS STUDY

This study is a 3-year design experiment (Collins, Joseph, & Bielaczyc, 2004) aimed at evaluating the possibility and means by which Grade 4 students can assume collective responsibility for sustained knowledge advancement. It examines the social structures that evolved over 3 years in a Grade 4 classroom that implemented knowledge-building pedagogy supported by Knowledge Forum. The analyses focus on (a) the effectiveness of the different social structures in enabling collective cognitive responsibility, particularly whether the third iteration, involving much greater opportunism in social organization and emergent goals, results in the highest level of collective cognitive responsibility; and (b) how the different designs for collaboration affect students' knowledge gains.

This study was conducted in the Institute of Child Study at the University of Toronto. Inquiry-based learning is integral to the school's educational program; the adoption of knowledge-building pedagogy and Knowledge Forum helps to build on this tradition and move beyond it. The participants in this study were three classes of fourth graders—22 students each year—taught by the same teacher, who is an author of this article. The three classes were equivalent in demographic composition and prior academic performance as evaluated through a standard test. The students of the first cohort were using Knowledge Forum for the first school year, with the other two cohorts using it for the second year. However, the Year 1 students also had rich experience with inquiry-oriented teaching; before participating in the present research, they had become acquainted with Knowledge Form through a knowledge-building initiative on a different topic that had lasted 2 months.

Over the 3 years of this investigation, the teacher worked with the three classes studying optics in their science curriculum, using approximately 4 months in each year. The optics study integrated face-to-face and online knowledge-building processes. Classroom discussions and offline activities helped to frame and give definition to online work in Knowledge Forum. For example, students discuss diverse ideas through face-to-face, knowledge-building discourse—referred to as "KB Talk" (Knowledge-Building Talk) by the students—conduct experiments and observations to advance their theories, search libraries and the Internet for reference material, and spend a great deal of time reading. They record and share new resources and discoveries in Knowledge Forum and engage in sustained online discourse to advance their understanding. Thus, the software serves as a notebook, repository, and space to develop, interact around, and continually improve their ideas—their community knowledge (screenshots from Year 3 are provided in Figure 1).

Each successive year represented an effort to implement knowledge building more effectively, with the focal principle collective responsibility for community knowledge (Scardamalia, 2002). The researchers assisted the teacher in developing and refining classroom designs, collecting feedback data, and dealing with technical issues, with the teacher and his students playing a primary role in identifying and elaborating classroom processes needed to advance their knowledge.

DESIGNS IMPLEMENTED IN THE 3 YEARS

When reporting a design experiment that involves multiple phases, authors generally describe their designs and corresponding results phase by phase. Considering the fact that the characteristics of the collaboration frameworks adopted in the 3 years, as well as the advances they enabled, can only be clearly understood through their comparisons, we decided in the present article to elaborate the evolution of the designs in one section and follow this with an aggregated report of the results.

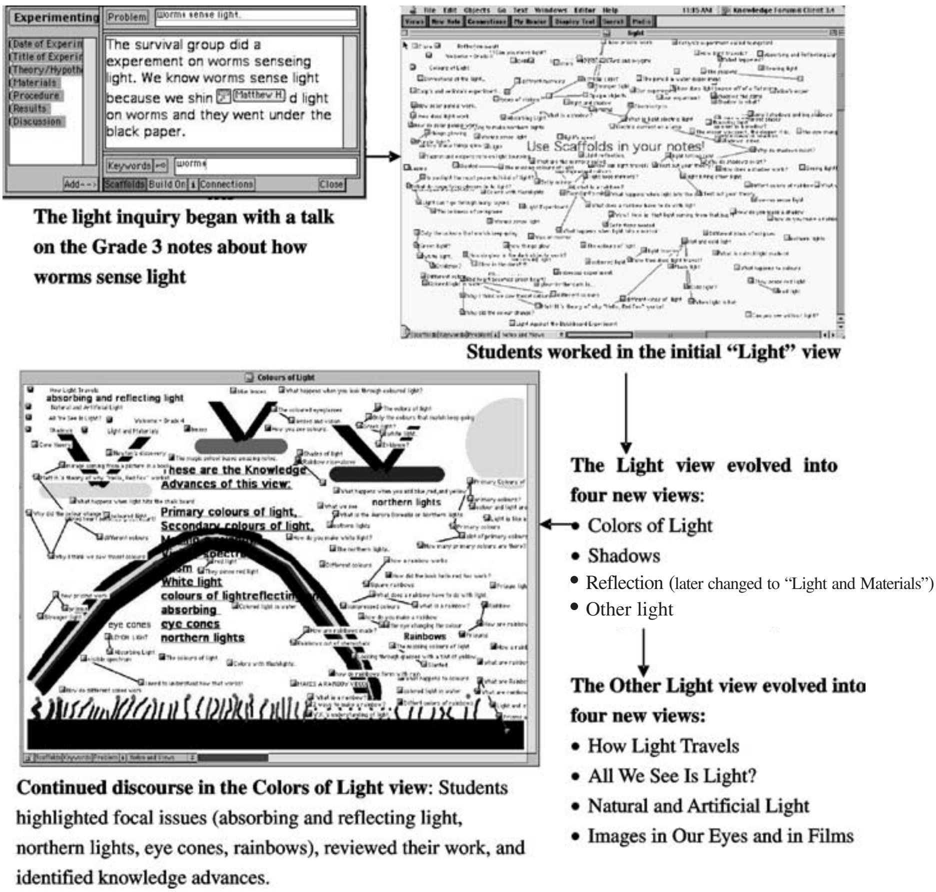


FIGURE 1 The emergent process of knowledge building under the opportunistic-collaboration design. Each square icon in a view (e.g., Colors of Light) represents a note. A line between two notes represents a build-on.

More detailed accounts and analyses are provided for the design of the third year, because it represents a new approach that has not been empirically tested in the educational literature.

Year 1

In the first year, students and the teacher worked together to identify areas of interest. Students were divided into six groups based on these interests, and correspondingly they worked in six views in Knowledge Forum: Sources of Light, Images, Angles and Reflection, Colors of Light, Colors of Opaque Objects, and Mirrors. Within these areas of specialization, students directed the inquiry processes. Students in each group identified and read useful materials, using a folder to organize their materials. They conducted experiments to test their ideas and wrote notes in their Knowledge Forum view to share and develop their ideas and indicate what they needed to better understand. Near the end of the inquiry, each small group summarized major knowledge advances evident in its Knowledge Forum view. Every student wrote an individual portfolio note to summarize what he or she had learned about light; this strategy was also used in Years 2 and 3.

The teacher tried to be an authentic member of the community rather than the dominant knowledge provider. He brought problems of understanding to the discussions, observed how the understanding was advancing in the classroom, helped to direct to where the information might be located, provided opportunities for the group to make appropriate discoveries by designing and/or conducting an experiment, and encouraged students to reflect on their methods of investigation. However, working with multiple fixed groups, he often faced the need to coordinate the division of labor by assigning specific inquiry tasks to different groups and highlighting important issues of inquiry. As is elaborated in "Outcomes," this was partly done through the questions he raised in the workspaces of the small groups.

As the knowledge building proceeded, the teacher noticed that most students only read notes in the views of their own groups. When he mentioned this to students, they indicated that they did not have time to read and build on the work of other team members, although they would have liked to. It is interesting that they were aware of small-group structures impeding their efforts to become more engaged with a broader network of colleagues and ideas. As mentioned earlier, the same was found to be the case in a Fostering Communities of Learners classroom (A. L. Brown & Campione, 1996). In the Brown and Campione context, the design refinement was a new form of knowledge sharing known as crosstalk. In the current context, in Year 1, the design refinement led to the teacher encouraging and providing students time to read one another's notes and to have more classroom conversation about advances of different groups. However, as elaborated below and suggested in "Outcomes," more elaborate structures were needed to maximize opportunities for collective responsibility for community knowledge.

Year 2

In the second year, and again based on discussion of research interests, students were organized into six groups, each of which created a view in Knowledge Forum: Vision, Light Frequency, Materials, Physics of Light, Images, and Lenses. As in Year 1, each group engaged in inquiry into a special area. The social organization accommodated cross-group note reading but extended the framework to ensure more than knowledge sharing. For example, students who were working on different problems were encouraged to design experiments that might address the larger network of problems represented in their different lines of work. In Year 2, the teacher also provided time for the students to write notes in peer groups' views and to add helpful new information, references from readings, comments, ideas arising from their research, and so forth. The fact that students understood that the challenge was to go beyond knowledge sharing was reflected in their growing concern for addressing integrative concepts. They were responsible for another design change: The community needed to "approve" the research interests of each group to ensure that they were aligned with the class's goal.

With students possibly contributing to all views while specializing in one area, the teacher increasingly noticed the importance of creating a psychologically safe culture. Through classroom discussions, he helped students realize that they did not need to feel overly attached to a specific theory, as theories and ideas can be adopted, criticized, and developed by peers within their group and by other groups. In science broadly, currently accepted theories are the ones with the best supporting evidence, but there are other, perhaps better theories that have yet to be developed and tested. Members in a community can collectively own their problems and ideas and work together to improve them.

As the teacher's observation and related data analyses (see "Outcomes") showed, the interacting group design helped to connect the work of different groups to enable collective advancement of understanding. However, under this framework, the collaboration still lacked flexibility, and the teacher still needed to coordinate the small groups and mediate their interactions. As he reflected, "I spend a lot of time saying what you're going to be doing, OK, go, come back, tell me what you did.… There wasn't enough fluidity."

Year 3

In the third year, the teacher abandoned the fixed small-group structure altogether in favor of all students starting with the same shared, top-level goal (i.e., to understand optics). The students elaborated subgoals as their work proceeded. The resultant interconnected network of views, in the order generated, were Light, How Light Travels, Colors of Light, Light and Materials, Natural and Artificial Light, Shadows, Images in our Eyes and in Film, and All We See Is Light (see Figure 1). No one was assigned to work in specific Knowledge Forum views; students were responsible for the growth of all views. On a daily basis, they were free to explore any problem from any view. Small teams formed, disbanded, and regrouped, and full-class conversations convened, at the volition of community members based on perceived needs for different social and discourse structures to advance their understanding of optics. Students engaged in individual note writing and reading; small-group cooperative reading, experiments, and reviews of knowledge advance; and whole-class knowledge-building talks. They often and spontaneously proposed how they should proceed (e.g., “We need to have a KB Talk about …” “We need to conduct an experiment on …”) by talking to the teacher or the class or by dropping a note in an envelope on the wall. The unfolding processes are summarized in Figure 1 and detailed below. An excerpt from the teacher’s reflection journal is included in the Appendix to elaborate what happened in one class.

The Year 3 light inquiry began with a classroom conversation that focused on a Grade 3 Knowledge Forum database built by the same students a year earlier on a diferent topic. Students recalled their experiments investigating worms in a science unit and they wanted to review their work on how worms sense light. They showed much enthusiasm in revisiting their earlier work for issues that they wanted to continue to explore, and they commented that they should study light in greater detail. In the classroom talk they mentioned a number of phenomena in which they were interested: fireflies, solar panels, glow-in-the-dark materials, artificial and natural light, and mirrors and reflection. They created a Light view in Knowledge Forum and started to record their questions and theories there. In the 2 weeks that followed, students worked in this single view, researching issues identified previously. New issues emerged and were also added to the view: shadows, rainbows and colors, light and vision, light refraction and absorption, lasers, northern lights, and so forth.

In the third week, realizing that this single view was getting too “messy,” students proposed that they create more views in Knowledge Forum to accommodate their notes. Through another classroom talk, students reviewed their various lines of inquiry and identified focal themes for further study. They suggested titles for new views, with the result that they created four new views: Colors of Light (e.g., rainbow, northern lights), Shadows, Reflection, and Other Light (for any other notes). The notes in the initial Light view were copied into the four new views. Each view was hyperlinked to all other views for easy navigation. At that point, students suggested that they form small groups working in different views—a process learned in Grade 3. The teacher resisted this proposal, proposing that the whole class work as a single group, with each student feeling free each day to research any problem from any view.

As their work proceeded, the “Other Light” view evolved into four new views: How Light Travels, All We See Is Light?, Natural and Artificial Light, and Images in Our Eyes and in Films. Their knowledge-building discourse took them deeper into their various theories and problems of understanding represented in each view. This led to the realization that each inquiry involved various subissues. To represent the evolving goals, students created subsections within each view. For example, the Colors of Light view shown in Figure 1 was framed into four clusters: absorbing and reflecting light, northern lights, eye cones, and rainbows. Knowledge Forum provided students with a flexible view–subview structure that made it possible for them to highlight evolving goals for all members of the community and reorganize their notes accordingly.

To promote student reflection as their work progressed, and to engage students in going beyond idea diversity to coherence—or what is more popularly known to students as "rising above"—the teacher initiated discussions about "what are our knowledge advances." Following a discussion, students voluntarily formed into temporary groups, each of which adopted a view; read all of the notes in the view; identified the problems and knowledge advances; and recorded them in their rise-above, knowledge advances section of the view (see the Colors of Light view in Figure 1 as an example). For major lines of inquiry, students additionally created rise-above notes to summarize specific knowledge advances and elaborate how they had achieved those advances. In doing so, they noticed that some lines of their inquiry were relatively weak and spontaneously started to engage in deeper inquiry of relevant issues.

DATA ANALYSES

Our data analyses examined the impact of the designs on the functioning of the community as a whole, as well as on knowledge advances of the individuals, with students' discourse in Knowledge Forum as the primary data source. At the community level, we analyzed the social network patterns that emerged from the online interactions and content analyses of teacher–student exchanges. Additional, in-depth analyses were conducted for the third year to understand the evolution of the community knowledge space under a more emergent collaboration design. Measures at the individual level focused on students' individual portfolio notes, which summarized what they had learned through the light inquiry.

Examining Collective Cognitive Responsibility Based on Online Discourse

To provide empirical measures of collective cognitive responsibility, we analyzed discourse in Knowledge Forum according to the three dimensions of collective responsibility:

1. *Awareness of contributions.* In the online environment, students develop awareness of their community (e.g., knowing the members, emergent issues, ideas, and their connections) by reading notes in the community knowledge space. We analyzed note-reading contacts (i.e., who read whose notes) in each year.
2. *Complementary contributions.* Knowledge Forum allows users to link to one another's notes through building on, rising above, and referencing/citing the work of other authors. This study examines students' collaborative

efforts by analyzing links between notes, as well as conceptual connections—co-contributing to a conceptual thread of inquiry.

3. *Distributed engagement.* This was indicated by the degree of equality or variance among members, as well as the specific roles played by students and their teacher in the knowledge-building discourse.

These measures are elaborated below and summarized in Table 1. These analyses were supplemented with teacher reflections recorded in a journal that he kept for the 3 years of this study and in a 20-min interview in which he was asked to reflect on his role as a teacher and the advances he had made.

The analyses of online discourse involved a set of measures adopted from social network analysis (SNA; Wasserman & Faust, 1994). SNA provides methods for examining information flow in a community or organization based on mathematical graph theory. A social network consists of nodes and lines among them, with each community member represented as a node and a relational tie (e.g., building on) between two members as a line. A variety of SNA indicators can be used to examine the holistic patterns of a network (e.g., density, centrality, subcommunity structures) as well as the positions of individual members within it (e.g., in-degree, out-degree, power; Hanneman, 2001). Using the SNA software NetMiner II (Cyram, 2004), we applied SNA to the Knowledge Forum log files, which provided data for two types of social relationships: (a) who read whose notes and (b) who linked to whose notes (i.e., created build-ons, rise-aboves, or references). The note-reading and -linking relationships in each year were represented as valued case-by-case (member-by-member) matrices that indicated the frequencies of

TABLE 1
Specific Analyses of Collective Cognitive Responsibility Enacted by Students in the Online Space

Effort	*Specific Analyses*
Awareness of contributions	Percentage of notes and percentage of inquiry threads read per student; density of the note reading as reflected in who read whose notes.
Complementary contributions	Percentage of notes linked through building on, rising above, or referencing other authors; density of the note-linking network reflected in who linked to whose notes; cliques as reflected in note linking; coparticipation in different inquiry threads (for the third year only).
Distributed engagement	Centralization measures that indicate degree of inequality or variance among members in a network; analyses of teacher–student exchanges; analysis of students' roles in inquiry threads (for the third year only).

note-reading and -linking contacts between each pair of participants. Specific measures are elaborated along with the results.

To understand how the teacher and his students shared their control over the knowledge-building discourse, we analyzed patterns of teacher–student exchanges. Using content analysis (Chi, 1997), the first author read and reread the teacher's notes together with the conversation threads in which the teacher's notes were embedded and identified major categories of content, as elaborated in "Outcomes."

Year 3 represented the high point for collective responsibility of community knowledge, and so, to anticipate findings, we conducted an additional "inquiry threads" analysis (Zhang, 2004; Zhang, Scardamalia, Lamon, Messina, & Reeve, 2007) for database entries from Year 3. The goal was to gain a deeper understanding of students' inquiry processes—and the evolution of their community knowledge space—when they were taking more responsibility for ideas within the community space as a whole. Analysis of online entries typically focuses on patterns of interactions (e.g., question–answer or idea–comment exchanges). Inquiry threads analysis, in contrast, organizes online discourses into conceptual streams according to the focus of the inquiry. We identified inquiry threads by reading through all of the notes in the Knowledge Forum views and tracing the problems that were worked on by students. Notes addressing the same problem were clustered into a semantically related thread representing a distinct line of inquiry. To gauge reliability, two raters independently coded the notes in the Shadows view. They independently identified the principal problems addressed in this view (e.g., nature of shadows, sizes of shadows, eclipses, and sundials) with full agreement and clustered the notes under these principal problems with an interrater consistency of 83%.

Analyses of Knowledge Gains Based on Students' Portfolio Notes

Assessing student understanding through their reflective essays has been used and validated in a number of studies (e.g., Lee, Chan, & van Aalst, 2006; van Aalst & Chan, 2007; Zhang et al., 2007). In this analysis, we divided each student's portfolio note into idea units—the smallest unit of text that conveyed a distinct idea regarding optics. Each idea was coded according to a coding scheme (see Table 2 for details). The analyses focused on two issues: knowledge diffusion and depth of understanding.

Knowledge diffusion. This analysis looked at whether the knowledge-building process featured with a higher level of collective cognitive responsibility could enable more dynamic idea spread (A. L. Brown et al., 1993) and increase individual students' knowledge gains about diverse inquiry themes. To this end, we analyzed students' knowledge gains in relation to inquiry themes that had emerged over the 3 years. We first read the notes in the Knowledge Forum databases and

TABLE 2
Coding Scheme for Ideas in Portfolio Notes

Category	*Subcategory and Defining Features*	*Example*
Inquiry theme—portfolio	An idea unit in a student's portfolio indicating knowledge gained about an inquiry theme.	Nature of shadows: "The umbra is the darkest part of the shadow."
Epistemic complexity of ideas	1. *Unelaborated facts:* Description of terms, phenomena, or experiences without elaboration.	"The umbra is the darkest part of the shadow."
	2. *Elaborated facts:* Elaboration of terms, phenomena, or experiences.	"The angle of incidents equals the angle of reflection, that means if you shine a light source on a flat mirror then the angle you shine the light on the mirror is the angle it will reflect."
	3. *Unelaborated explanations:* Reasons, relationships, or mechanisms mentioned without elaboration.	"Shadows are made when light hits an opaque object and so then it makes shadow. The shadow is always attached to an opaque object."
	4. *Elaborated explanations:* Reasons, relationships, or mechanisms elaborated.	"A shadow is made by an object in front of a light stream. The light can't go around and then no light get behind the objects and it's dark."
Scientific sophistication of ideas	1. *Pre-scientific:* Misconception; naive conceptual framework.	"I think shadows exist because they show you things are there. Everything has a shadow unless it's underground."
	2. *Hybrid:* Misconceptions that have incorporated scientific information but show mixed misconception/scientific frameworks.	"A shadow is sunlight that reflects off your body and makes almost the same shape but at different times either its smaller or bigger. In the morning I think that the shadow is bigger and when it comes close to night your shadow gets smaller …"
	3. *Basically scientific:* Ideas based on scientific framework but not precisely scientific.	"… if there is no light, there can't be a shadow."
	4. *Scientific:* Explanations that are consistent with scientific knowledge.	"… a shadow is created by the sun or artificial light hitting an opaque object. Shadows change size either depending on the size of the object or the light source, say the sun's position …"

identified 25 principal inquiry themes that were common to the 3 years, including how light travels, the nature of shadows, eclipses, rainbows, primary and secondary colors, lenses, lasers, cameras, and so forth. Then, each idea unit in a portfolio note was coded in relation to these themes (see Table 2 for an example).

Depth of understanding. Each idea unit was rated in terms of epistemic complexity and scientific sophistication. *Epistemic complexity* indicates students' efforts to produce not only descriptions of the material world but also theoretical explanations and articulation of hidden mechanisms central to the nature of science (Salmon, 1984). A 4-point scale (1 = *unelaborated facts*, 2 = *elaborated facts*, 3 = *unelaborated explanations*, and 4 = *elaborated explanations*) adapted from Hakkarainen's (2003) work was used to code each idea unit. Two raters independently coded 20% of the portfolio notes to assess interrater reliability, which was found to be 0.88 (Pearson correlation).

Optics is a domain that often leads to young students demonstrating a broad array of naïve conceptions (Galili & Hazan, 2000). To assess *scientific sophistication*—the extent to which a student has moved from an intuitive toward a scientific framework—we coded students' ideas in their portfolio notes on a 4-point scale (1 = *pre-scientific*, 2 = *hybrid*, 3 = *basically scientific*, and 4 = *scientific*). This coding was informed by Galili and Hazan's facets-scheme framework for analyzing misconceptions in optics. Two raters independently coded 20% of the portfolio notes, resulting in an interrater reliability of 0.89 (Pearson correlation).

Epistemic complexity represents the level of complexity at which a student chooses to approach an issue. The higher the complexity, the larger the proportion of cognitive effort required. Scientific sophistication represents the level of success a student has achieved in processing an idea at a certain complexity level. It is relatively easy to convey a scientific idea at a factual level (e.g., "We see afterimages when …") but harder to provide a scientific explanation (e.g., elaborate causes of afterimages). The meaning of the scientific score of an idea is dependent on the level of its complexity. Therefore, we generated a composite score to indicate the depth of understanding by multiplying the two ratings, weighting the rating of scientific sophistication with the level of complexity. For example, an idea rated as 1 (*unelaborated facts*) and 4 (*scientific*) would have a composite score of 4, whereas an idea rated as 4 (*elaborated explanations*) and 4 (*scientific*) would have a composite score of 16.

OUTCOMES

Developing Awareness of the Community Through Note Reading

In a social network, members are shown as nodes, and connections between nodes are represented by lines. Density is reflected in the number of lines divided by the maximum number of all possible lines, with a value varying between 0 and 1. In a knowledge-building community with high-level collective cognitive responsibility, members should learn about the ideas in the communal space, resulting in a dense note-reading network. In this study, the analyses of note-reading contacts (i.e., who read whose notes) resulted in densities of 0.97, 0.95, and 0.99 for the 3 years, respectively, without significant difference ($p > .10$). These consistently high densities indicate that each year almost all members read one another's notes. From Year 1 on, there appeared to be a commitment to this basic "awareness" aspect of collective responsibility. But as the teacher noted in his reflection journal, working in fixed groups in Year 1 led students to only read notes of their own groups until the teacher explicitly discussed with them reading other notes and provided time for them to read notes from peers in other groups. In the second and especially third years, community-wide note reading became a spontaneous and consistent behavior, as it was essential to the knowledge-building process.

Complementary Contributions: Note-Linking Contacts

Density of note linking. Over the 3 years, each student created an average of 17.10 (SD = 6.15), 15.60 (SD = 7.88), and 18.41 (SD = 6.66) notes in Knowledge Forum. To gauge their complementary efforts, we examined the extent to which they built onto, rose above, and referenced one another's notes. We refer to these in combination as students' *note-linking contacts*. Table 3 reports the percentages of notes that were linked and the densities of the note-linking networks for Years 1 through 3. To distinguish teacher-mediated collaboration from peer-to-peer collaboration, we computed note-linking densities for whole-community networks (including the teacher) and student-only networks. Analyses of variance (ANOVAs) revealed that the different designs had significant effects on the note-linking densities, including the densities of the whole communities, $F(2, 66) = 9.54$, $p < .001$, $\eta^2 = 0.22$; and those of the student networks, $F(2, 63) = 17.84$, $p < .001$, $\eta^2 = 0.36$. As the multiple comparisons using the least significant difference (LSD) method indicated, whether or not the teacher was included, the

TABLE 3
Note-Linking Contacts Under the Three Designs

Year	*Linked Notes (%)*	*Density of the Network, Including the Teacher, M (SD)*	*Density of the Student Network, M (SD)*
Year 1	43.80 (12.33)	0.19 (0.12)	0.14 (0.04)
Year 2	49.20 (15.33)	0.36 (0.21)	0.30 (0.17)
Year 3	33.80 (13.93)	0.41 (0.18)	0.40 (0.19)

Note: Note-linking connections included building on, rising above, and referencing.

densities of Year 3 ($p < .001$) and Year 2 ($p = .001$) were significantly higher than that for Year 1. Even though the average percentage of linked notes in the first year was quite high (43.80%), the students tended to create links to notes authored by members of their own groups, resulting in the lowest density. Working under the interacting group design and the opportunistic-collaboration design, students built on, rose above, and referenced notes from a broader network of "players." There was no significant Year 2 to 3 difference for the whole community (including the teacher; $p > .10$), but there was a significant difference in the note-linking densities of student networks ($p < .05$). Relative to Year 2, Year 3 showed more direct student collaboration and, correspondingly, less mediation by the teacher.

Clique analyses of the note-linking contacts. To further examine complementary efforts, we used clique analysis, which provides a closer look at subcommunity structures. In a social network, similar actors are tied together by socializing bonds of interaction through which they come to share beliefs and behavioral tendencies (Burt, 1991). A *clique* in a network can be defined as "a sub-set of a network in which the actors are more closely and intensively tied to one another than they are to other members of the network" (Hanneman, 2001, p. 79). Our analyses used the strongest definition of a clique, which is a maximal subcommunity whose members have all possible ties present among themselves—a "maximal complete subgraph" in mathematical terms. A study by Aviv, Erlich, Ravid, and Geva (2003) suggested the usefulness of clique analysis for probing interaction patterns in online communities. To measure collective cognitive responsibility, this study looked at the number of cliques in the note-linking network each year, how separate these cliques were, and whether particular members (e.g., the teacher) acted as nodes that bridged different cliques. In a knowledge-building community with high collective responsibility, there should emerge a larger number of overlapping cliques instead of a few isolated subgroups that divide the network and the ideas contained there. The teacher should not be the only actor who connects different subnetworks.

Results of the clique analyses are shown in Table 4 and Figure 2. The sociograms in Figure 2 also indicate the status of the various members with respect to their engagement in the work of the community. The greater influence a member has, the more central his or her position.

This analysis helped to distinguish and visualize three models of collaboration, corresponding to the 3 years of this study; these are labeled, respectively, fixed groups, interacting groups, and opportunistic collaboration. As Table 4 shows, six cliques were identified in the note-linking network of the first year (see Figure 2a), when a fixed groups model was adopted; these six subcommunities corresponded to the six research groups set up in the classroom. Of the 22 students, 21 belonged to one clique only. This, together with the high value of the Cohesion Index, indi-

TABLE 4
Clique Analysis of Knowledge Forum Databases: Years 1, 2, and 3

Year	*Total Cliques*	*Average Size of Cliques, M (SD)*	*Mean Cohesion Index,*[a] *M (SD)*	*No. of Cliques Each Student Belongs To, M (SD)*	*No. of Cliques the Teacher Belongs To*
Year 1	6	4.67 (0.52)	10.83 (7.21)	1.05 (0.21)	5
Year 2	25	6.00 (0.70)	2.68 (1.12)	5.68 (4.45)	25
Year 3	61	5.74 (1.08)	1.78 (0.36)	15.18 (11.48)	16

[a]The Cohesion Index assesses the extent to which there are intensive interactions within a clique rather than outside of it. The higher the Cohesion Index, the more distant and isolated the cliques.

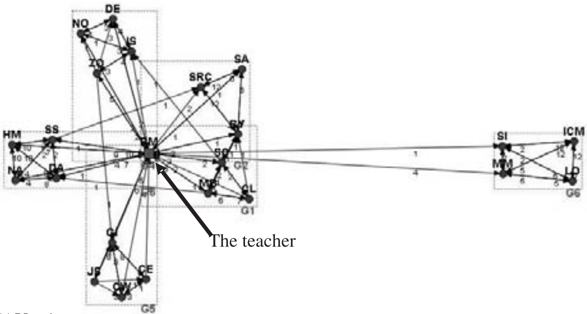
cates that members in each research group demonstrated intensive note-linking contact with one another but rarely built on, rose above, or referenced notes of members of other groups. The teacher assumed the central position, as the sole member, belonging to five cliques.

In the network of the second year (see Figure 2b), many more cliques ($N = 25$) were detected, with an average size of six members. Each student belonged to 5.68 cliques on average. The Cohesion Index was much lower than for the first year, suggesting that the students had interacted with a broader network of members during the knowledge-building discourse. As an example, members in vision and lens groups worked together to understand near- and far-sightedness and corrective glasses. However, there was a clear division between central and peripheral students. The teacher again held a central position, being a member in all of the 25 cliques.

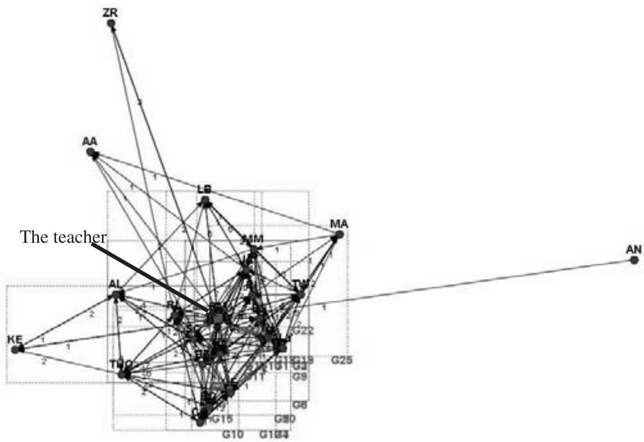
A much more distributed, coherent network structure was observed in the third year (see Figure 2c). There were 61 cliques altogether, with each student belonging to 15.18 cliques on average. The teacher was much less central in this network, belonging to 16 cliques, which is equivalent to the number of cliques an average student belonged to.

Centrality of the Note-Linking Networks

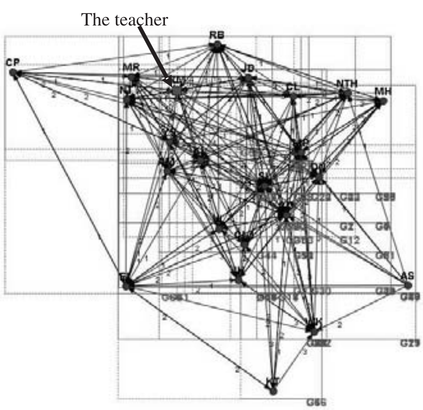
To specifically measure the degree of centralization (inequality) of the note-linking networks, we computed Freeman's graph centralization measures. The most centralized or unequal possible network is a star-shaped network in which one actor assumes the central position and has relational ties to all other actors, whereas any other actor has a tie only to this central actor. Freeman's graph centralization indices express the degree of inequality of a network as a percentage of a perfect star network of the same size (Hanneman, 2001). In this study, because the relational ties in the note-linking networks were directed (e.g., "A referencing B's notes" differs from "B referencing A's notes"), we analyzed centrality based on



(a) Year 1



(b) Year 2



(c) Year 3

FIGURE 2 Clique structures of the note-linking networks. A node represents a member identified with a code. A line between two nodes denotes a note-linking relation between two members, the direction and frequency of which are represented by the arrow and the value on the line. The more information flow a member carries, the more central he or she is displayed in a network.

in-degree (receiving contacts) and out-degree (making contacts to others). As Table 5 shows, the centralization measures of the first 2 years were quite high, indicating that the degree of centralization/inequality of these networks was more than 50% or even 60% of the theoretical maximum (i.e., a star-shaped network), suggesting that the power of individual actors varied rather substantially in the networks (Hanneman, 2001). The centralization measures of the third year were much smaller, implying that positional advantages were more equally distributed. These results coincide with the findings of the clique analyses, indicating that the opportunistic-collaboration design is more in favor of distributed collaboration and collective engagement.

Patterns of Teacher–Student Exchanges

This analysis provided content-based accounts for the sharing of power (influence) between the teacher and his students in their knowledge-building discourse. Ubiquitous to traditional classrooms is a pattern of teacher–student–teacher turns (Cazden, 2001), in which the teacher initiates a conversation by asking a question, which is followed by a response from a student, and which then terminates with evaluative feedback from the teacher (Lemke, 1990; Mehan, 1979; Sinclair & Coulthard, 1975). In the present study, the teacher served as an active community member in each year's discourse, contributing ideas to raise the level of the discourse and providing suggestions for further experimentation, reading, planning, and so on required to carry that discourse forward. In the majority of his notes, he posed questions to students. These questions fell into two categories: "questions *for* ideas" and "questions *on* ideas."

Questions for ideas. This type of question is common to traditional classroom discourse, which starts with the teacher's question. By creating an initial note, the teacher identifies a new concept or inquiry and asks students to generate understandings, explanations, or plans. In Year 1, the teacher posted a question in the "Colors of Opaque Objects" view: "I need to understand: why plastic shopping

TABLE 5
Freeman's Graph Centralization Measures of Note-Linking Networks Across 3 Years

Design	*In (Receiving Links)*	*Out (Linking to Others)*
Year 1: Fixed groups	56.20%	56.20%
Year 2: Interacting groups	53.10%	62.60%
Year 3: Opportunistic collaboration	38.43%	33.68%

Note: The graph centralization measures were computed based on degrees of receiving and sending out note-linking contacts. The higher the measures the more centralized the network.

bags are usually white. Is there a good reason for the color? Does the color affect the food inside the bag somehow?" This note led to eight responses from the Colors group, including the following three:

> SS: I think shopping bags are white because … that color stands out.
>
> HM: … I have not found out yet but I think plastic shopping bags are white because if they were black the food inside would be very hot.
>
> DA: The white in the shopping bag reflects the sunlight so that the food doesn't go bad.

As this teacher-initiated question suggests, the teacher facilitates the work of small groups by asking questions and highlighting new issues.

Questions on ideas. Building on to a student's idea, the teacher poses a question. For example, in a note, a student mentioned that worms can sense light. Building onto this note, the teacher wrote, "I thought worms do not have eyes, so then how do they sense light?" By raising this question, the teacher conveys interest in the student's contribution and offers additional input that might help clarify or deepen an idea initiated by a student, rather than directing the student to a new area of inquiry.

Figure 3 shows the proportion of notes that included each type of questions in the 3 years. Chi-square tests examining proportions of the two types of questions across the 3 years revealed significant increases in questions *on* ideas, $\chi^2(2) = 8.87$, $p < .05$, which deepen student-initiated inquiries. Correspondingly, there was a dramatic drop in questions *for* ideas, $\chi^2(2) = 21.78$, $p < .001$, which direct students to new lines of inquiry. The pattern of teacher–student interaction in a given year was the direct result of the personal decisions made by the teacher and his students on an ongoing basis, with the goal of achieving optimal outcomes. However, their personal regulation of participation was shaped by the social activity system in which they were working. A social system with a flexible, opportunistic framework of collaboration encourages more symmetry in teacher–student exchanges (Tabak & Baumgartner, 2004) and dynamic information flow among students, giving rise to a higher level of collective responsibility.

The Evolution of the Community Knowledge Space in the Third Year

The opportunistic collaboration of the third year led to the highest level of collective cognitive responsibility, according to all measures. To understand the evolution of the community knowledge space along the collaboration process—as well as how

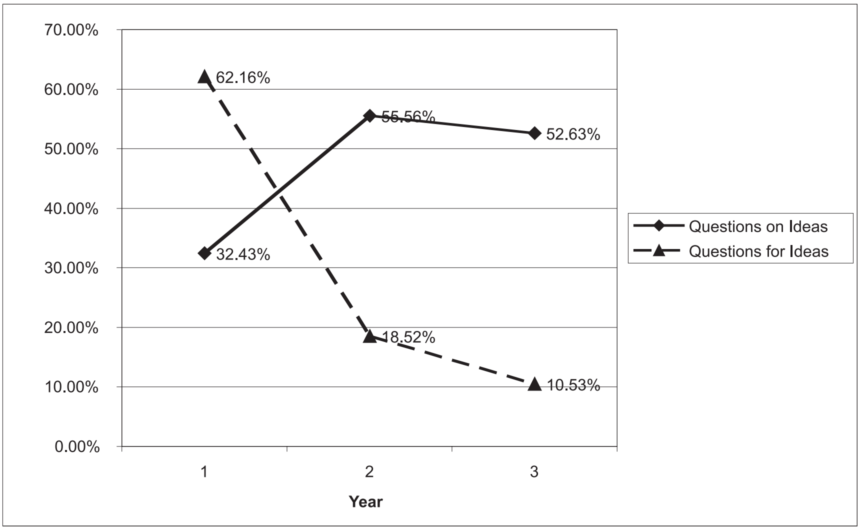


FIGURE 3 Two types of questions raised in the teacher's notes in the Knowledge Forum database: Years 1, 2, and 3. "Questions for ideas" lead to teacher-initiated discourse, and "questions on ideas" deepen student-initiated inquiry.

the members participated in different aspects of this space—we applied inquiry threads analysis to the knowledge-building discourse of Year 3. A total of 28 principal themes were addressed in student discourse (e.g., nature of shadows, sizes of shadows, eclipses, rainbows, primary and secondary colors). Each theme had its own conceptual stream of discourse or inquiry thread, lasting from the first to the last note.

It is interesting that all of the 28 inquiry threads were initiated by students, with 16 of the 22 students initiating at least one inquiry thread. Soon after a specific student theory, problem of understanding, question, or so on emerged in the community space, other students "built on." On average, each inquiry thread engaged 7.52 ($SD = 4.92$) students as writers and 18.07 ($SD = 4.48$) as readers (all writers were also readers). Every student contributed to multiple inquiry threads as an author ($M = 9.91$, $SD = 2.52$), including a few threads in which there was deep involvement and threads in which he or she was an occasional contributor. Although participation patterns in inquiry threads do not map directly onto clique structures identified by SNA (SNA represents a more basic level of linking interactions), a correlation analysis revealed a strong relationship between the number of cliques a student belonged to and the number of inquiry threads he or she participated in as a writer (Pearson $r = .58$, $p = .001$). Students who contributed to more inquiry threads were members of more cliques.

Analysis of discourse in each inquiry thread indicated progressive advances of community knowledge. In an inquiry thread, students generated ideas and evidence, brought in new information from reading materials, and progressively worked on deeper questions as they deepened their understanding. For example, in the inquiry of rainbows, the students initially talked about how rainbows are made, leading them to the understanding that the rain droplets split sunlight to make a rainbow. Then they generated further problems, such as the following: How can a big thing like a rainbow "be activated by mere raindrops"? "There are lots of colors of the rainbows, why are they always in the same order?" "Why do rainbows always take the shape of a semicircle?" Sustained inquiry of one theme led students to deeper understanding and directed them into the inquiries of other interrelated problems, with new and more demanding concepts coming to the fore as they conducted their research. These inquiries covered all of the required topics listed in the Ontario Curriculum of Science and Technology for Grade 4, as well as many topics expected for Grade 8 (e.g., light waves, color vision, colors of opaque objects, concave and convex lenses). Qualitative rating of student-contributed ideas in each thread on a 4-point scale (1 = *pre-scientific*, 2 = *hybrid*, 3 = *basically scientific*, and 4 = *scientific*) indicated significant improvement over time, moving from an intuitive framework toward scientific understanding. Specific results, together with a visual representation of the unfolding inquiry threads, were presented in a recent article (Zhang et al., 2007). Partly due to the amount of work involved in analyses of inquiry threads, we did not apply this analysis to the databases of the first 2 years.

Individual Knowledge Gains

We evaluated individual knowledge gains based on students' portfolio notes, focusing on knowledge diffusion and depth of understanding.

Knowledge diffusion. We analyzed students' knowledge gains in relation to inquiry themes that had emerged over the 3 years in Knowledge Forum. As Table 6 shows, the mean number of inquiry themes about which a student reported knowledge gains in his or her portfolio note increased along the 3 years: ANOVA ($F(2, 63) = 64.14$, $p < .001$, $\eta^2 = 0.88$). Post hoc comparisons using the LSD method showed a significantly larger number of inquiry themes addressed in each portfolio note for Year 2 ($p < .01$, Cohen's $d = 0.81$) and 3 ($p < .001$, Cohen's $d = 3.64$) than Year 1, as well as for Year 3 compared to Year 2 ($p < .001$, Cohen's $d = 2.26$). As we expected, by strengthening collective cognitive responsibility, a knowledge-building community could achieve more dynamic knowledge diffusion, helping students benefit from knowledge advances of the whole community.

TABLE 6
Evaluation of Students' Knowledge Advances Summarized in Their Portfolio Notes

Design	*Number of Inquiry Themes Addressed*	*Depth of Understanding*[a]
Year 1: Fixed groups	7.64 (2.11)	4.80 (0.94)
Year 2: Interacting groups	9.82 (3.17)	5.21 (1.04)
Year 3: Opportunistic collaboration	16.45 (2.69)	5.72 (0.70)

Note: Data are *M* (*SD*).

[a]Each idea unit was rated on two scales in terms of epistemic complexity (1 = *unelaborated facts*, 2 = *elaborated facts*, 3 = *unelaborated explanations*, 4 = *elaborated explanations*) and scientific sophistication (1 = *pre-scientific*, 2 = *hybrid*, 3 = *basically scientific*, 4 = *scientific*). The composite score of depth of understanding was computed by multiplying these two ratings.

It is interesting that an analysis of the writing styles of the portfolio notes found that in the first and second year, students often explicitly identified research groups that "owned" various knowledge advances. For example, in his portfolio note, SC wrote: "In the images group I found out something called a pin hole camera … In the lenses group I learn that there['re] different kinds of lenses … In the vision group I learned that pupils get bigger in the dark because …" From the students' perspective, the knowledge space reflected a "division of labor" framework rather than ideas to be understood and improved collectively and placed in coherent relation to one another. None of the portfolio notes in the third year involved this style of writing.

Depth of understanding. Each idea unit in a portfolio note was further rated in terms of epistemic complexity and scientific sophistication, and the depth of understanding was decided by the multiplication of these two measures (see Table 6). An ANOVA revealed a significant effect for the different designs on the depth of understanding, $F(2, 63) = 5.69$, $p < .01$, $\eta^2 = 0.15$. Multiple comparisons using the LSD method indicated that students of Year 3 scored significantly higher than those of Year 1 ($p = .001$, Cohen's $d = 1.11$) and marginally significantly higher than students of Year 2 ($p = .063$, Cohen's $d = 0.58$), with no significant difference between Years 2 and 1 ($p > .10$). In addition to its benefits on knowledge diffusion, the knowledge-building process with a higher level of collective cognitive responsibility also encouraged students to seek better and deeper understanding of issues in a domain. In particular, the distributed, flexible social interactions enabled by the Year 3 approach were conducive to knowledge advancement, with students identifying important issues at the intersection of diverse lines of inquiry and rising above this diversity to produce more coherent, sophisticated, and interconnected explanations.

DISCUSSION

The Three Models of Collaborative Knowledge Work

Through Social Network Analysis (SNA) and qualitative analysis of online discourse, we examined the collaborative knowledge-building designs that evolved over 3 years in a Grade 4 classroom. We characterized these as a fixed groups model, an interacting groups model, and an opportunistic-collaboration model. The first two models represent two variants of the small-group approach that dominates collaborative inquiry in schools. The opportunistic-collaboration model is a new design largely dependent on the creation of a community space for ideas and in line with an emergent, social perspective of knowledge creation (Sawyer, 2003, 2007; Valsiner & Veer, 2000). A broad range of analyses indicated improvement in collaboration and knowledge advances over the years.

The interacting groups model outperformed the fixed groups model on a number of measures, with students connected to a broader network of members and ideas. Congruent with Roth and Bowen's (1995) finding, cross-group interactions enabled better knowledge diffusion at the classroom level. Beyond information sharing, the Year 2 small groups also worked together to identify and address issues of shared interests. For example, the vision group and the lenses group collaborated to investigate near-sightedness, resulting in new insights. However, the interacting groups model still shared with the fixed groups model a relatively centralized framework of engagement, with the teacher mediating students' interactions and coordinating the work of different groups. Similar issues were observed in project-based science classrooms where small groups were adopted (Singer, Marx, Krajcik, & Chambers, 2000).

Compared to the fixed and interacting small group designs, the opportunistic-collaboration model led to more pervasive, flexible, distributed collaborations, and greater diffusion of information and knowledge advances, with each student engaged in multiple inquiry threads to help advance the knowledge of the whole community. There is a natural concern that the less structured, opportunistic framework may mostly benefit high-achieving students, thus increasing between-student variation. However, the analyses of note contribution, note-linking density, knowledge diffusion, and depth of understanding showed that the between-student variation in Year 3 was not larger than in the first 2 years and was even noticeably smaller on the measure of deep understanding. Analysis of pre- and posttest data collected in Year 3, which was reported in Zhang et al. (2007), showed significant improvement in optics knowledge among both high- and low-achieving students.

This opportunistic-collaboration framework did not preclude the use of small groups, as students often gathered in smaller groups, based on perceived need, to discuss a reading selection, conduct an experiment, discuss findings they had trouble explaining, and so forth. But unlike the other models, the opportunistic-collaboration model provided students with the freedom and responsibility to group and regroup flexibly in the service of emergent goals. Students moved between small-group and whole-class structures and redefined their inquiries and participatory roles to address idea diversity and build coherence. Their contact with these diverse ideas (e.g., images, cameras, vision) helped them to monitor gaps in the community space, formulate new inquiry goals, and develop coherent accounts. Although this high-level control and negotiation of action has also been observed in small-group-based inquiry (e.g., Roth & Bowen, 1995), in those environments dynamic negotiation and knowledge coconstruction is within small groups, with the whole community focusing mostly on knowledge sharing. With the support of a communal knowledge space, the flexible, opportunistic-collaboration design can raise the collaborative control to the whole-class level. Highly structured collaboration can limit students' engagement in high-level, creative discourse (Cohen, 1994; Dillenbourg, 2002; Kollar, Fischer, & Hesse, 2006). Progressive knowledge building extended over weeks, months, or years can be better supported through distributed, opportunistic collaboration, which helps to seed the learner into the "ever-changing dynamic so he or she can become his or her own participant in the flow" (Barab et al., 1999, p. 371). Year 2 results suggest that important advances can be gained from encouraging cross-group interactions, even in circumstances in which opportunistic collaboration is difficult (A. L. Brown & Campione, 1996; Roth & Bowen, 1995).

As formative, design-based research, this study cannot tease out the effect of the teacher's natural growth from intentional efforts to create a knowledge building environment in which students assume collective cognitive responsibility for knowledge advancement. The observed changes were the result of a combination of factors, including the collaboration framework and the specific strategies used to make that framework effective. However, comparing the results of the present study to observations of similar knowledge-building classrooms suggests that the reported advances should be largely attributed to purposeful designs. Prior to the introduction of "collective responsibility for community knowledge" as an explicit knowledge-building principle, a study by Hewitt (1996) traced the 4-year progress of a Grade 5/6 knowledge-building teacher. This teacher used a small-group design in each of the 4 years—along with indications of student knowledge advances that increased each year. Students' within-group interaction was found to increase over the 4 years, but the same was not true for their cross-group interaction. In this previous study, as well as the current one, teacher growth is evident, and in each case social interaction patterns appear to make important differences. The present study suggests that student advances can be additionally enhanced through a more opportunistic, flexible collaboration framework that engages collective responsibility for the knowledge productivity of the community as a whole.

Important Design Issues Related to Opportunistic Collaboration

Achieving greater opportunism in classroom structures and behaviors should not be confused with laissez-faire conditions, lack of timelines, absence of deadlines, and so forth. Such a situation could lead to loss of control rather than greater responsibility. An important factor in enabling greater flexibility and responsibility in this study is the communal knowledge space, a knowledge medium very much attuned to enabling teachers to turn over responsibility to students with confidence—at least more confidence than might be the case under other conditions. In Knowledge Forum all contributions are recorded, so there is clear accounting for what different individuals and teams are bringing to the community. Furthermore, contributions are evident to all, not just the teacher, so irresponsible behavior is likewise evident to all. The suite of analytic tools underlying Knowledge Forum makes it possible to track individual and group contributions. The teacher—or students, if the teacher wishes —has continual and easy access to feedback such as rate of contribution, amount of writing, increases in vocabulary, and so forth. And because students build on the work of one another, they come to depend on one another to advance the discourse, to enter ideas in a timely way, to check accuracy of information, and so forth. This creates a system of social pressure, and the teacher no longer needs to be the primary taskmaster. Participants are actively involved in helping to set goals, deadlines, timelines, peer review, monitoring of advances, revising goals, and so forth. These structures are then better attuned to knowledge work than to arbitrary and externally defined constraints on work.

With the support of an electronic environment for knowledge building, the teacher needs to develop specific designs to facilitate effective opportunistic collaboration, making collective cognitive responsibility a social norm. The Year 3 analysis highlighted a number of strategies.

Individual commitment to community knowledge and shared goals. As soon as the top-level goal emerges in a community, it is important to make sure that all members clearly understand this goal and are held accountable for achieving it. The teacher in this study accomplished this by beginning with a single Knowledge Forum view that identified the shared, top-level goal. Students coconstructed the mission statement, and they were encouraged to develop and participate in both online and offline knowledge-building processes to fulfill their mission. As work proceeded, they continually linked their new inquiries and discoveries to this view.

Representation of Emergent Subgoals and Evolving Community Knowledge

This was made possible by student and teacher use of Knowledge Forum. Knowledge Forum provides a communal space for representing new goals and subgoals as they emerge, using flexible and revisable views to show their ever-expanding and interconnected knowledge spaces. It supports knowledge-building discourse in these views, with student ideas at the center.

Micro and macro processes. Distributed, opportunistic collaboration with high-level collective cognitive responsibility is sustained by mutual interaction between individual actions and collective social structures—known as "the micro-macro link" (Sawyer, 2002): Individual participation and interaction gives rise to community, which in turn influences individual behavior. Distributed frameworks for social interaction within the community emerge from individual actions and interactions, with causal influence on individuals (Sawyer, 2002, 2003), sustaining members to participate in the ongoing knowledge-building practice, as a persistent pattern. In a knowledge-building community, it is important to nurture the emergence of the community knowledge space as a coconstructed social structure, with the norm of individual and coauthored contributions to a communal enterprise, with all contributions sensible and understandable to all members. The members can then navigate through the community knowledge space and adapt their different contributions accordingly. This can be partly done by engaging students in meta-discourse so that their collective work becomes the object of classroom discussions. In the third year of this design experiment, the teacher occasionally initiated face-to-face knowledge-building talks to serve as a model for the sorts of conversations students might initiate on their own. Through these talks, the community members collectively reviewed their work recorded in Knowledge Forum, often with their views projected onto a screen. They identified significant knowledge advances, defined and redefined focal knowledge problems, organized and reorganized major strands of inquiry, and used various features of Knowledge Forum (e.g., views, hyperlinks between views, background pictures of views) to give shape to their communal knowledge space. Students worked in this evolving knowledge space, moving between their work in specific content areas and their reading of the knowledge space for the community as a whole. The cognitive and social dynamics that the teacher elaborated for the community helped to channel students' creative energy to achieve their collective knowledge goal.

What Does Opportunistic Collaboration Require of the Teacher?

Implementing opportunistic collaboration requires the teacher to reconceptualize his or her role and work with emergent, interactional processes.

Deep trust in student agency. The teacher in this study is dedicated to developing a "feeling of empowerment" among his students—a feeling that they are able to contribute to knowledge advancement. He builds his confidence to believe that a flexible, collectively evolving knowledge-building process can work out—in his words, to believe "that I can begin without having a structure in mind, that I can really involve the children in the design of it. In fact, it is the other way around; they involve me in their design."

Working with emergence. The teacher adjusted his notion of control in classroom from a "factory model" of structuring and managing student activities toward an "organic model" of working with emergence and flow toward collective understanding. He said:

> I learned to really have to face what students do … So the students thought they were reading an article about something, then new question appeared. They could actually go and do something else. So as a teacher I have to learn that it's OK to say, "I'm not sure what that group is doing." I can go and find out and ask them … I realize students are usually on task, and they are able to go deeply, because they have been given that opportunity to do that.

Progressive curriculum, continual idea improvement. With the adoption of opportunistic collaboration comes this teachers' deep understanding of the progressive and unfolding nature of curriculum:

> I used to be worried about … covering curriculum … Now I truly believe that the curriculum … is about the process and how deeply the children go. And as a result, anything can be curriculum. It could be something that comes from the younger grades, as easily as it's from, you know, a higher grade, as long as it's an area where you can go deeply … I know what the concepts are. I have to know. But I also know that we might go deeper than my own understanding is.

When planning and facilitating knowledge building, the teacher first identifies big ideas and important problems in a domain as well as possible connections with related areas. He imagines the knowledge-building process in an open way and engages student collective responsibility to evolve specific goals and processes. The teacher focuses on understanding the evolution of student thinking, bringing important new ideas emergent in the community space to student focus, "stirring the pot" by asking stimulating questions, and facilitating meta-discourse about what they have achieved and what needs to be done. His efforts are supported by a school community that engages intensive professional discourse through which teachers talk about their problems and advances and share plans, actions, and reflections (for a detailed analysis of this school, see Zhang & Scardamalia, 2007; Zhang, Hong, Teo, Scardamalia, & Morley, 2008). An ongoing research goal is to further understand the role of the teacher in collectively evolving knowledge-building processes.

CONCLUSIONS AND NEXT STEPS

By examining the social structures and processes that evolved over 3 years in a classroom, this study suggests that a flexible, opportunistic-collaboration framework can give rise to high-level collective cognitive responsibility and dynamic knowledge advancement. Deep inquiry-based learning extended over a long period needs to go beyond fixed, small-group collaboration to embrace more improvisation and opportunism. Additional studies are needed in a variety of school contexts to explore design strategies for enhancing effective opportunistic collaboration to determine how, and with what success, different teachers might engage students in more flexible and opportunistic arrangements.

Knowledge Forum played an important role in enabling students' collective responsibility for knowledge building through the communal knowledge spaces and discourse tools it provided. In a community space with diverse emergent inquiries and flexible participation, a design challenge is to help students understand the changing status of their community knowledge and the actions and interactions taking place at the community level (see also Kimmerle, Cress, & Hesse, 2007), both in spaces where they are key contributors and areas in which they are "learners" or occasional contributors. The most recent version of Knowledge Forum focuses on addressing this challenge through concurrent feedback. We are experimenting with the use of automated measures of community dynamics—such as those tested in the present study—as means of providing feedback as work proceeds. With positive results, these community feedback tools will help a broader range of classrooms to engage dynamic knowledge-building practice together with a trajectory of continual improvement.

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REFERENCES

Amar, A. D. (2002). *Managing knowledge workers: Unleashing innovation and productivity.* Westport, CT: Quorum Books.

Aviv, R., Erlich, Z., Ravid, G., & Geva, A. (2003). Network analysis of knowledge construction in asynchronous learning networks [Online]. *Journal of Asynchronous Learning Networks, 7*(3).

Barab, S., Cherkes-Julkowski, M., Swenson, R., Garrett, S., Shaw, R. E., & Young, M. (1999). Principles of self-organization: Learning as participation in autocatakinetic systems. *Journal of the Learning Sciences, 8,* 249–390.

Bell, P., & Linn, M. C. (2000). Scientific arguments as learning artifacts: Designing for learning from the web with KIE. *International Journal of Science Education, 22,* 797–817.

Bereiter, C. (2002). *Education and mind in the knowledge age.* Mahwah, NJ: Erlbaum.

Bereiter, C., & Scardamalia, M. (1993). *Surpassing ourselves.* Chicago: Open Court.

Bereiter, C., & Scardamalia, M. (in press). Toward research-based innovation. In F. Benavides (Ed.), *Emerging models for learning and innovation.* Paris, France: Organisation for Economic Co-Operation and Development.

Bielaczyc, K., & Collins, A. (2006). Fostering knowledge-creating communities. In A. M. O'Donnell, C. E. Hmelo-Silver, & G. Erkens (Eds.), *Collaborative learning, reasoning, and technology* (pp. 37–60). Mahwah, NJ: Erlbaum.

Brown, A. L., Ash, D., Rutherford, M., Nakagawa, K., Gordon, A., & Campione, J. C. (1993). Distributed expertise in the classroom. In G. Salomon (Eds.), *Distributed cognitions* (pp. 188–228). New York: Cambridge University Press.

Brown, A. L., & Campione, J. C. (1996). Psychological theory and design of innovative learning environments: On procedures, principles, and systems. In L. Schauble & R. Glaser (Eds.), *Innovations in learning: New environments for education* (pp. 289–325). Mahwah, NJ: Erlbaum.

Brown, J. S., & Duguid, P. (2000). *Social life of information.* Boston: HBS Press.

Burt, R. S. (1991). *Structure: A general purpose network analysis program, reference manual.* New York: Columbia University.

Cazden, C. B. (2001). *Classroom discourse: The language of teaching and learning* (2nd ed.). Portsmouth, NH: Heinemann.

Chatzkel, J. L. (2003). *Knowledge capital.* New York: Oxford University Press.

Chi, M. T. H. (1997). Quantifying qualitative analysis of verbal data: A practical guide. *Journal of the Learning Sciences, 6,* 271–315.

Chinn, C., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education, 86,* 175–218.

Cohen, E. G. (1994). Restructuring the classroom: Conditions for productive small groups. *Review of Educational Research, 64*(1), 1–15.

Collins, A., Joseph, D., & Bielaczyc, K. (2004). Design research: Theoretical and methodological issues. *Journal of the Learning Sciences, 13,* 15–42.

Csikszentmihalyi, M. (1999). Implications of a systems perspective for the study of creativity. In R. J. Sternberg (Eds.), *Handbook of creativity* (pp. 313–335). Cambridge, England: Cambridge University Press.

Cusumano, M. A. (2001). Focusing creativity. In I. Nonaka & T. Nishiguchi (Eds.), *Knowledge emergence* (pp. 111–123). Oxford, England: Oxford University Press.

Cyram. (2004). *NetMiner II. Version 2.5.0.* Seoul, South Korea: Author.

Davis, B. G. (1993). *Tools for teaching.* San Francisco: .

De Leede, J., Nijhof, A. H., & Fisscher, O. A. (1999). The myth of self-managing teams: A reflection on the allocation of responsibilities between individuals, teams and the organization. *Journal of Business Ethics, 21,* 203–215.

Dillenbourg, P. (2002). Over-scripting CSCL: The risks of blending collaborative learning with instructional design. In P. A. Kirschner (Eds.), *Three worlds of CSCL: Can we support CSCL* (pp. 61–91). Heerlen, The Netherlands: Open Universiteit Nederland.

Engeström, Y. (2008). *From teams to knots: Activity-theoretical studies of collaboration and learning at work.* New York: Cambridge University Press.

Engle, R. A., & Conant, F. R. (2002). Guiding principles for fostering productive disciplinary engagement: Explaining an emergent argument in a community of learners classroom. *Cognition and Instruction, 20,* 399–483.

Galili, I., & Hazan, A. (2000). Learners' knowledge in optics: Interpretation, structure and analysis. *International Journal of Science Education, 22*(1), 57–88.

Gates, D. (2005, September 11). Boeing 787: Parts from around world will be swiftly integrated. *The Seattle Times*.

Gloor, P. A. (2006). *Swarm creativity: Competitive advantage through collaborative innovation networks.* Oxford, England: Oxford University Press.

Hakkarainen, K. (2003). Progressive inquiry in a computer-supported biology class. *Journal of Research in Science Teaching, 40,* 1072–1088.

Hanneman, R. A. (2001). *Introduction to social network methods.* Riverside: University of California, Riverside, Department of Sociology.

Herrenkohl, L. R., & Guerra, M. R. (1998). Participant structures, scientific discourse, and student engagement in fourth grade. *Cognition and Instruction, 16,* 431–473.

Hewitt, J. G. (1996). *Progress toward a knowledge-building community.* Unpublished doctoral thesis, University of Toronto, Ontario, Canada.

Kimmerle, J., Cress, U., & Hesse, F. W. (2007). An interactional perspective on group awareness: Alleviating the information-exchange dilemma (for everybody?). *International Journal of Human-Computer Studies, 65,* 899–910.

Kollar, I., Fischer, F., & Hesse, F. W. (2006). Collaboration scripts—A conceptual analysis. *Educational Psychological Review, 18,* 159–185.

Koschmann, T. (2002). Dewey's contribution to the foundations of CSCL research. In G. Stahl (Ed.), *Computer support for collaborative learning: Foundations for a CSCL community: Proceedings of CSCL 2002* (pp. 17–22). Boulder, CO: Erlbaum.

Lamon, M., Secules, T., Petrosino, A. J., Hackett, R., Bransford, J. D., & Goldman, S. R. (1996). Schools for thought: Overview of the international project and lessons learned from one of the sites. In L. Schauble & R. Glaser (Eds.), *Contributions of instructional innovation to understanding learning* (pp. 243–288). Hillsdale, NJ: Erlbaum.

Lee, E. Y. C., Chan, C. K. K., & van Aalst, J. (2006). Students assessing their own collaborative knowledge building. *International Journal of Computer-Supported Collaborative Learning, 1,* 277–307.

Lehrer, R., Carpenter, S., Schauble, L., & Putz, A. (2000). Designing classrooms that support inquiry. In J. Minstrell & E. V. Zee (Eds.), *Inquiring into inquiry learning and teaching in science* (pp. 80–99). Washington, DC: American Association for the Advancement of Science.

Lemke, J. L. (1990). *Talking science: Language, learning, and values.* Norwood, NJ: Ablex.

Leonard-Barton, D. (1995). *Wellsprings of knowledge.* Boston, MA: Harvard Business School Press.

Mehan, H. (1979). *Learning lessons.* Cambridge, MA: Harvard University Press.

Nonaka, I., & Takeuchi, H. (1995). *The knowledge-creating company.* Oxford, England: Oxford University Press.

Orlikowski, W. J. (2002). Knowing in practice: Enacting a collective capability in distributed organizing. *Organization Science, 13*(3), 249–273.

Paavola, S., & Hakkarainen, K. (2005). The knowledge creation metaphor—An emergent epistemological approach to learning. *Science & Education, 14,* 535–557.

Palincsar, A. S., Anderson, C. W., & David, Y. (1993). Pursuing scientific literacy in the middle grades through collaborative problem solving. *Elementary School Journal, 5,* 643–658.

Reiser, B. J., Tabak, I., Sandoval, W. A., Smith, B. K., Steinmuller, F., & Leone, A. J. (2001). BGuILE: Strategic and conceptual scaffolds for scientific inquiry in biology classrooms In S. M. Carver & D. Klahr (Eds.), *Cognition and instruction: Twenty-five years of progress* (pp. 263–305). Mahwah, NJ: Erlbaum.

Resnick, L. B., & Hall, M. W. (2001). *The principles of learning: Study tools for educators* (Version 2.0) [CD-ROM]. Pittsburgh, PA: University of Pittsburgh, Institute for Learning, LRDC.

Roth, W. M., & Bowen, G. M. (1995). Knowing and interacting: A study of culture, practices, and resources in a Grade 8 open-inquiry science classroom guided by a cognitive apprenticeship metaphor. *Cognition and Instruction, 13,* 73–128.

Salmon, W. C. (1984). *Scientific explanations and the causal structure of the world.* Princeton, NJ: Princeton University Press.

Sawyer, R. K. (2002). Emergence in psychology: Lessons from the history of non-reductionist science. *Human Development, 45,* 2–28.

Sawyer, R. K. (2003). Emergence in creativity and development. In K. Sawyer, V. John-Steiner, S. Moran, S. Sternberg, D. H. Feldman, J. Wakamura, et al. (Eds.), *Creativity and development* (pp. 12–60). Oxford, England: Oxford University Press.

Sawyer, R. K. (2004). Creative teaching: Collaborative discussion as disciplined improvisation. *Educational Researcher, 3*(2), 12–20.

Sawyer, R. K. (2007). *Group genius: The creative power of collaboration.* New York: Basic Books.

Scardamalia, M. (2002). Collective cognitive responsibility for the advancement of knowledge. In B. Smith (Eds.), *Liberal education in a knowledge society* (pp. 67–98). Chicago: Open Court.

Scardamalia, M. (2004). CSILE/Knowledge Forum®. In A. Kovalchick & K. Dawson (Eds.), *Education and technology: An encyclopedia* (pp. 183–192). Santa Barbara, CA: ABC-CLIO.

Scardamalia, M., & Bereiter, C. (1994). Computer support for knowledge building communities. *Journal of the Learning Sciences, 3,* 265–283.

Scardamalia, M., & Bereiter, C. (2006). Knowledge building: Theory, pedagogy, and technology. In K. Sawyer (Ed.), *Cambridge handbook of the learning sciences* (pp. 97–118). New York: Cambridge University Press.

Scardamalia, M., Bereiter, C., McLean, R. S., Swallow, J., & Woodruff, E. (1989). Computer supported intentional learning environments. *Journal of Educational Computing Research, 5,* 51–68.

Sinclair, J. M., & Coulthard, R. M. (1975). *Towards an analysis of discourse: The English used by teachers and pupils.* London: Oxford University Press.

Singer, J., Marx, R. W., Krajcik, J., & Chambers, J. C. (2000). Constructing extended inquiry projects: Curriculum materials for science education reform. *Educational Psychologist, 35*(3), 165–178.

Tabak, I., & Baumgartner, E. (2004). The teacher as partner: Exploring participant structures, symmetry, and identity work in scaffolding. *Cognition and Instruction, 22,* 393–429.

Thagard, P. (1992). *Conceptual revolutions.* Princeton, NJ: Princeton University Press.

Valsiner, J., & Veer, R. V. D. (2000). *The social mind.* Cambridge, England: Cambridge University Press.

van Aalst, J., & Chan, C. K. K. (2007). Student-directed assessment of knowledge building using electronic portfolios in Knowledge Forum. *Journal of the Learning Sciences, 16,* 175–220.

Wasserman, S., & Faust, K. (1994). *Social network analysis: Methods and applications.* Cambridge, England: Cambridge University Press.

Weick, K. E., & Roberts, K. (1993). Collective mind in organizations: Heedful interrelating on flight decks. *Administrative Science Quarterly, 38,* 357–381.

Wells, G. (2002). Learning and teaching for understanding: The key role of collaborative knowledge building. In J. Brophy (Ed.), *Social constructivist teaching: Affordances and constraints* (pp. 1–41). Oxford, England: Elsevier/JAI Press.

Wenger, E. (1998). *Communities of practice: Learning, meaning, and identity.* New York: Cambridge University Press.

Wertsch, J. V. (1998). *Mind as action.* New York: Oxford University Press.

Williams, W. M., & Yang, L. T. (1999). Organizational creativity. In R. J. Sternberg (Ed.), *Handbook of creativity* (pp. 373–391). Cambridge, England: Cambridge University Press.

Zhang, J. (2004, March). *The growing networks of inquiry threads in a knowledge building environment.* Paper presented at the Knowledge Building Summer Institute, Ontario Institute for Studies in Education, University of Toronto, Canada.

Zhang, J., Hong, H.-Y., Teo, C., Scardamalia, M., & Morley, E. (2008, April). *"Constantly going deeper": Knowledge building innovation in an elementary professional community.* Paper presented at the annual meeting of American Educational Research Association, New York, NY.

Zhang, J., & Scardamalia, M. (2007, April). *Sustaining principle-based knowledge building innovation at an elementary school.* Paper presented at the annual meeting of American Educational Research Association, Chicago, IL.

Zhang, J., Scardamalia, M., Lamon, M., Messina, R., & Reeve, R. (2007). Socio-cognitive dynamics of knowledge building in the work of nine- and ten-year-olds. *Educational Technology Research and Development, 55*(2), 117–145.

APPENDIX

The following excerpt from the teacher's reflection journal exemplifies the flexible participation and collaboration in Year 3. On an ongoing basis, students identified emergent issues and weak aspects in their inquiry, generated plans, and organized themselves to implement their plans (e.g., review their advances, conduct experiments, identify and read materials) using a variety of social structures (individual work, small-group collaboration, whole-class talk) to achieve their goals.

> Thursday:
>
> Students … state that it is difficult to find what the knowledge advances from each light view [in Knowledge Forum] are. We come up with the idea of "view masters," students who would volunteer to "adopt" a view, read all the notes and then record on the background of the view all the big ideas of the view …
>
> Two students are experimenting with diffraction grating to try to prove that light travels in waves.
>
> Three boys are working on an experiment that involves a propeller suspended in a jar … The hypothesis is that the propeller will turn when placed in front of sunlight …
>
> Some students are working on [cooperative reading] after realizing that the view they were "masters" of did not contain clear knowledge on a concept, e.g. fluorescence.
>
> [*Note:* These small groups formed spontaneously. The teacher highlighted issues and plans proposed by the community, but he did not group the students or assign tasks to them.]
>
> …
>
> Students continued to work on views [in Knowledge Forum]. SL worked on the "All we see is light" view … WK and KT adopted the "How light travels" view and simply listed the theories we have about light travel.
>
> We had a quick [knowledge-building] talk … because three groups working on experiments wanted to present knowledge advances and problems of understanding from their findings. One group placed a card with a narrow slit in front of a glass of water and shone a flashlight through it. A color spectrum was evident … KL suggested that water, as in rain, acts as a prism to create [a] rainbow. Rich discussion on

why the card and slit were necessary. YS followed with an experiment she found in a book—to understand how images are turned up side down in a camera using a shoebox, tracing paper, a paper tube and a magnifying lens … SL said he had read that the same thing occurs in our eyes, that in essence she had created a model of an eye with the magnifying lens being the pupil and the tracing paper being the retina. (SL had just completed a Knowledge Forum note on how lenses correct near and far-sightedness.) JD added that an experiment she did at home was to create a "pin-hole camera" and she found the same results and will bring it in on Monday. We did not get to the final experiment involving the propeller—postponed to next week's [knowledge-building] talk.