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**Designs for Collective Cognitive Responsibility in Knowledge Building Communities**

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Abstract

This article reports a design experiment conducted over three successive school years, with the goal of having young students assume increasing levels of collective responsibility for advancing their knowledge, as represented in their contributions to a communal knowledge space. The context is a Grade 4 classroom; designs for studying optics are co-constructed by the teacher and students attempting to create classroom practices conducive to sustained knowledge building. 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 for advancing student knowledge corresponding to the following organizations: (a) Year 1—fixed small-groups; (b) Year 2—interacting small-groups working together throughout their knowledge work; and (c) Year 3—opportunist-collaboration, with small teams forming and disbanding under the volition of community members, based on emergent goals that arose as they addressed their shared, top-level goal of refining their knowledge of optics. The third-year model maps most directly onto the organic and distributed social structure in real-world knowledge-creating organizations, with Knowledge Forum software supporting the production and refinement of the community’s knowledge. Among the three designs, the opportunistic-collaboration model resulted in the highest level of collective cognitive responsibility, knowledge advances, and dynamic diffusion of information. It is argued that to enculturate youth into a knowledge-creating culture, classroom practice needs
to go beyond fixed small-groups to encourage distributed, opportunistic collaboration. Pedagogical and technological innovations to facilitate opportunistic collaboration are discussed.
Designs for Collective Cognitive Responsibility in Knowledge Building Communities

Introduction

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 places more emphasis on social dynamics (e.g., 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 suggests 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). This design-based research examines the social structures evolved in a knowledge building classroom over three years—from fixed small-groups to interacting groups, and 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. The work reported here aims to support the claim that such high-level knowledge work can be
integral to schooling, starting in the middle elementary grades. Support for the broader claim that such work is feasible across a broader range of ages, SES 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 (Engle & Conant, 2002; Herrenkohl & Guerra, 1998; Lamon, Secules, Petrosino, Hackett, Bransford, & Goldman, 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 and 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 they are engaged in (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). 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). 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) 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 co-authoring notes that may include multimedia elements, students contribute ideas, models, problems, plans, data, etc. into 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 each other’s notes, and create rise-above notes and views to summarize, distill, 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; presenting evidence, data, and reference material; and so forth. Having this community knowledge space and related interaction tools helps to enable collective responsibility for knowledge advancement.

Collective cognitive responsibility is important in knowledge-based organizations of today (Nonaka & Takeuchi, 1995). An interesting example is the design of Boeing 787 aircraft, built by nearly 5,000 engineers (excluding production workers) distributed around the world. The design and engineering work took place simultaneously at multiple sites, over a long period of time, and yet all 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, sub-goals, and designs, with success dependent on all members rather than concentrated in the leader. They 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), and for the process as a whole. As issues emerge, they collectively shape next steps, build on each other’s strengths, and improve their ideas and designs. Their ability to “rise
above” current understandings to a higher plane is reflected in the 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 their 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 non-redundant 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, they build onto each other’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 turning over the highest level executive processes to “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/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 vs. flexible, emergent structure. These frameworks can be
characterized as: (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 timeframe, 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 the work that individual students or small teams have done separately is assembled in the end. This often necessitates a pre-specified culminating task, and a fixed stage-model of inquiry with a timeline for each stage, making clear who will do what, in what 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 what activities and tasks should be
carried out in what 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 sequenced approaches recognize the need for a more fluid process (Reiser, Tabak, Sandoval, Smith, Steinmuller, & Leone, 2001); they recommend these simplified approaches to 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. 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 (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 pre-decided 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.” (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 highlights 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 they are engaged in (Valsiner & Veer, 2000), and to re-define and participate in community practices to achieve their goals, with no participant solely setting the agenda (Barab, Cherkes-Julkowski, Swenson, Garrett, Shaw, & Young, 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).

The above review of 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 three-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 evolved over three 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-levels of collective cognitive responsibility; and (b) how the different designs for collaboration affect students’ knowledge gains.

This study was conducted in a laboratory school in 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. The participants in this study were three classes of fourth-graders—22 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 for the second year. However, the Year 1 students also had rich experience with inquiry-oriented teaching; before participating in the present research, they became acquainted with Knowledge Form through a knowledge building initiative on a different topic that lasted two months.

Over the three years of work reported, the teacher worked with the three classes to study optics in their science curriculum, using approximately four months in each year. The optical study integrated face-to-face and online knowledge building processes. Classroom discussions and offline activities help 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 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 Three Years**

When reporting a design experiment that involves multiple phases, authors generally describe their designs and corresponding results phase by phase. In the present article, considering the fact that the characteristics of the collaboration frameworks adopted in the three years, as well as the advances they enabled, can only be clearly understood through their comparisons, we decide to elaborate the evolution of the designs in one section, followed by an aggregated report of the results. More detailed accounts and analyses were 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/she had learned about light; and this strategy was also used in Year 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 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 the results, 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 like to. Interestingly, 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 (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, it led to the teacher encouraging and providing students time to read each other’s notes and more classroom conversation about advances of different groups. However,
as elaborated below and suggested in results, 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. Like in Year 1, each group directed their 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, 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 they were aligned with the class’ 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 are 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 Results) 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 (to understand optics). The students elaborated sub-goals 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 re-grouped, 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, reviews of knowledge advance; 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 dropping a note in a pocket on the wall. The unfolding processes are summarized through Figure 1 and detailed below. An excerpt from the teacher’s reflection journal is included in Appendix 1 to provide more information about what happened in one class.

Insert Figure 1 about here

The light inquiry of this year began with a classroom conversation that focused on a Grade 3 Knowledge Forum database built by the same students a year earlier. 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 commented that they should study light in greater detail. In the classroom talk they mentioned a number of phenomena they were interested in: 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 two weeks that followed, students worked in this single view, researching issues identified above. 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 should 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 to aid easy navigation. At that point, students suggested that they should form small groups working in different views—a process learned in Grade 3. The teacher resisted this proposal, proposing that the whole class should 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 sub-issues. 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 them with a flexible view-subview structure that
made it possible for them to highlight evolving goals for all members of the community, and re-organize 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 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 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 that 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, discourse in Knowledge Forum was analyzed according to the three dimensions of collective responsibility: (a) 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. (b) Complementary contributions. Knowledge Forum allows users to link to each other’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. (c) Distributed engagement, as 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 three years of this study, and a 20-minute interview that asked him 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, sub-community structures) as well as the positions of individual members in it (e.g., indegree, outdegree, 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, which indicate the frequencies of 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. Following content analysis (Chi, 1997), the first author read and re-read the teachers’ notes together with the conversation threads the teachers’ notes were embedded in, and identified major categories of content, as elaborated in Results.

To anticipate findings, Year 3 represented the high point for collective responsibility of
community knowledge, and so 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 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 the reliability, two raters independently coded the notes in the view “Shadows.” 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 inter-rater consistency of 83%.

Analyses of Knowledge Gains Based on Students’ Portfolio Notes

Assessing student understanding through their reflective essays has been used and validated by 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.

Insert Table 2 about here

(a) **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 (Brown, Ash, Rutherford, Nakagawa, Gordon, & Campione, 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 three years. We first read the notes in the Knowledge Forum databases, and identified 25 principal inquiry themes that were common to the three years, including how light travels, 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).

(b) **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 four-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 percent of the portfolio notes to assess inter-rater
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 four-point scale (1 - pre-scientific, 2 - hybrid, 3 - basically scientific, and 4 - scientific). This coding was informed by Galili and Hazan’s (2000) facets-scheme framework for analyzing misconceptions in optics. Two raters independently coded 20 percent of the portfolio notes, resulting in an inter-rater 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 proportion of cognitive effort he/she needs to devote into its processing. 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 above 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” will have a composite score of 4, while an idea rated as “4 - elaborated explanations” and “4 - scientific” will 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 a density of 0.97, 0.95 and 0.99 for the three years respectively, without significant difference (p > .10). These consistently high densities indicate that almost all members read each other’s notes, each year. From Year 1 on, there appears to be a commitment to this basic “awareness” aspect of collective responsibility. But as the teacher noted in his reflection journal, Year 1, working in fixed groups led students to only read notes of their own groups, until the teacher explicitly discussed with them, and provided time for them to read notes from peers in other groups. In the second, and especially third year, 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 three years, each student created an average number 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 each other’s notes. We refer to these in combination as their note
linking contacts. Table 3 reports the percentages of notes that are linked and the densities of
the note linking networks, Years 1-3. 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.

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 the teacher was included or not, the densities of Year 3 ($p < .001$) and Year 2 ($p =< .001$) were significantly higher than 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 2-3 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 sub-community 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 sub-community whose members have all possible ties present among themselves—a “maximal complete sub-graph” in a mathematical term. A study by Aviv and colleagues (Aviv, Erlich, Ravid, & 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 of each year, how separate these cliques are, and whether there are particular members (e.g., the teacher) who act as nodes that bridge 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 sub-groups that divide the network and ideas contained there. The teacher should not be the only actor who connects different sub-networks.

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 her/his position.
This analysis helps to distinguish and visualize three models of collaboration, corresponding to the three 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 (Figure 2a) when a fixed-groups model was adopted; these six sub-communities correspond to the six research groups set up in the classroom. Twenty-one of the 22 students belong to one clique only. This, together with the high value of the Cohesion Index, indicates that members in each research group demonstrated intensive note-linking contact with each other, but rarely built on, rose above, or referenced notes of members of other groups. The teacher assumes the central position, as the sole member, belonging to five cliques.

In the network of the second year (Figure 2b), many more cliques (N = 25) were detected, with an average size of six members. Each student belongs to 5.68 cliques on average. The Cohesion Index is much lower than 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 is a clear division between central and peripheral students. The teacher again holds a central position, being a member in all the 25 cliques.

A much more distributed, coherent network structure was observed in the third year (See Figure 2c). There are 61 cliques altogether, with each student belonging to 15.18 cliques on average. The teacher is much less central in this network, belonging to 16 cliques, which is equivalent to the number of cliques an average student belongs 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, while any other actor only has a tie 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, since the relational ties in the note linking networks are directed (e.g., “A referencing B’s notes” differs from “B referencing A’s notes”), we analyzed centrality based on in-degree (receiving contacts) and out-degree (making contacts to others). As Table 5 shows, the centralization measures of the first two years are quite high, indicating that the degree of centralization/inequality of these networks are more than 50% or even 60% of the theoretical maximum (i.e., a star-shaped network), suggesting that the power of individual actors varies rather substantially in the networks (Hanneman, 2001). The centralization measures of the
third year are much smaller, implying that positional advantages are 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.

Insert Table 5 about here

Patterns of Teacher-Student Exchanges

This analysis provides 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, followed by a response from a student, and terminated by 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, etc. required to carry that discourse forward. In the majority of his notes, he posed questions to students. These questions fell into two categories:

(a) “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 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.

(b) “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 direct them to a new area of inquiry.

Figure 3 shows the proportion of notes that included each type of questions in the three years.

_____________________

Insert Figure 3 about here
Chi-square tests to examine proportions of the two types of questions across the three years revealed significant increases in “questions on ideas” ($X^2 = 8.87, \text{df} = 2, p < .05$), which deepen student-initiated inquiries. Correspondingly, there was a dramatic drop in “questions for ideas” ($X^2 = 21.78, \text{df} = 2, p < .001$), 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 they were working in. 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 the members participated in different aspects of this space, we applied inquiry threads analysis to the knowledge building discourse of Year 3. Twenty-eight principal themes were addressed in student discourse (e.g., nature of shadows, sizes of shadows, eclipses, rainbows, primary and secondary colors, etc.), each with its own conceptual stream of discourse—inquiry thread, lasting from the first to the last note.
Interestingly, all the 28 inquiry threads were initiated by students, with 16 of the 22 students having initiated at least one inquiry thread. Soon after a specific student theory, problem of understanding, question, etc. 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 where there was deep involvement and threads in which he/she was an occasional contributor.

Although participation patterns in inquiry threads do not map directly onto clique structures identified by SNA (SNA represent 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 s/he participated in as a writer (Pearson r = 0.58, 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: 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 the required topics listed in The Ontario Curriculum of Science and Technology for Grade 4, as well as many topics expected for Grade 8, for instance, light waves, color vision, colors of opaque objects, concave and convex lenses. Qualitative rating of student-contributed ideas in each thread on a four-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, have been 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 two years.

**Individual Knowledge Gains**

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

(a) **Knowledge Diffusion.** We analyzed students’ knowledge gains in relation to inquiry themes that had emerged over the three years in Knowledge Forum. As Table 6 shows, the mean number of inquiry themes about which a student reported knowledge gains in his/her portfolio note increased along the three 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 ($p < .001$, $d = 3.64$)
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.

Interestingly, 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 reflects 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.

(b) 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 \((p = .063, \text{Cohen's } d = 0.58)\), with no significant difference between Year 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. Particularly, 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 and qualitative analysis of online discourse, we examined the collaborative knowledge building designs that evolved over the three years in the 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, 2004; 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 shares 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 above 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 increase 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 the first two years, and even noticeably smaller on the measure of deep understanding. Analysis of pre- and post-test data collected in Year 3, which was reported in Zhang et al., (2007), showed significant improvement of optical 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 re-group flexibly in the service of emergent
goals. They 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 co-construction 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) Even in circumstances where opportunistic-collaboration is
difficult, Year 2 results suggest that important advances can be gained from encouraging
cross-group interactions (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 designs for collective cognitive responsibility. 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 four-year progress of a Grade 5/6 knowledge building teacher. This teacher used a small-group design in each of the four years—along with indications of student knowledge advances that increased each year. Students’ within-group interaction was found to increase over the four 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, which 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. What enables
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 group. Further, 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 each other, they come to depend on each other 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 3analysis highlighted a number of strategies.

(a) 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 co-constructed 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.

(b) Representation of emergent sub-goals 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 sub-goals as they emerged, 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.

(c) 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 co-constructed social structure, with the norm of individual and co-authored 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 review 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 student 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/her role and work with emergent, interactional processes.
(a) 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.”

(b) Working with emergence: The teacher adjusted his notion of control in classroom, from a “factory model” of structuring and managing student activities towards an “organic model” of working with emergence and flow towards collective understanding. As 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.”

(c) Progressive curriculum, continual idea improvement: With the adoption of opportunistic-collaboration comes his 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 emerged 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 detailed analysis of this school, see Zhang & Scardamalia, 2007; Zhang, Scardamalia, Hong, Teo, & Elizabeth, 2008). An ongoing research 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 three 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 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 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. Our most recent upgrading of Knowledge Forum focuses on addressing this challenge through concurrent feedback. We are experimenting with use of automated measures of community dynamics—such as those tested in the present study—as means to provide 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.

Acknowledgements

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Toronto, for the insights, accomplishments and research opportunities enabled by their work.

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Appendix 1

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: The above 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.
Figures:

The light inquiry began with a talk on the Grade 3 notes about how worms sense light.

Continued discourse in the Colors of Light view: Students highlighted focal issues (absorbing and reflecting light, northern lights, eye cones, rainbows); reviewed their work and identified knowledge advances.

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.
(a) Year 1
(b) Year 2

Figure 2. Clique structures of the note linking networks. A node represents a member. 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 value on the line. The more information flow a member carries, the more central he/she is displayed in a network.

(c) Year 3
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.
Tables:

Table 1

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

<table>
<thead>
<tr>
<th>Efforts</th>
<th>Specific Analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Community awareness</td>
<td>Percentage of notes and percentage of inquiry threads read per student; density of the note reading as reflected in who read whose notes.</td>
</tr>
<tr>
<td>Complementary contributions</td>
<td>Percentage of notes linked through building-on, rising-above, or reference to other authors; density of the note linking network reflected in who linked to whose notes; cliques as reflected in note linking; Co-participation in different inquiry threads (for the third year only).</td>
</tr>
<tr>
<td>Distributed engagement</td>
<td>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).</td>
</tr>
</tbody>
</table>
Table 2

Coding scheme for ideas in portfolio notes.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Sub-categories and defining features</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inquiry theme - portfolio</td>
<td>An idea unit in a student’s portfolio indicating knowledge gained about an inquiry theme.</td>
<td>Nature of shadows: “The umbra is the darkest part of the shadow.”</td>
</tr>
<tr>
<td>Epistemic complexity of ideas</td>
<td>Unelaborated facts: Description of terms, phenomena, or experiences without elaboration.</td>
<td>The umbra is the darkest part of the shadow.</td>
</tr>
<tr>
<td></td>
<td>Elaborated facts: Elaboration of terms, phenomena, or experiences.</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td>Unelaborated explanations: Reasons, relationships, or mechanisms mentioned without elaboration</td>
<td>Shadows are made when light hits an opaque object and so then it makes shadow. The shadow is always attached to an opaque object.</td>
</tr>
<tr>
<td></td>
<td>Elaborated explanations:</td>
<td>A shadow is made by an object in front</td>
</tr>
<tr>
<td>Scientific Sophistication</td>
<td>1. Pre-scientific: Misconception; naive conceptual framework.</td>
<td>I think shadows exist because they show you things are there. Everything has a shadow unless it's underground.</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>2. Hybrid: Misconceptions that have incorporated scientific information but show mixed misconception/scientific frameworks.</td>
<td>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…</td>
</tr>
<tr>
<td></td>
<td>3. Basically scientific: Ideas based on scientific framework, but not precisely scientific.</td>
<td>… if there is no light, there can’t be a shadow.</td>
</tr>
<tr>
<td></td>
<td>4. Scientific: Explanations that are consistent with scientific knowledge.</td>
<td>… 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 …</td>
</tr>
</tbody>
</table>
Table 3

Note Linking Contacts under the Three Designs.

<table>
<thead>
<tr>
<th>Year</th>
<th>Percentage of linked notes</th>
<th>Density of the network, including the teacher</th>
<th>Density of the student network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1</td>
<td>43.80% (12.33%)</td>
<td>0.19 (0.12)</td>
<td>0.14 (0.04)</td>
</tr>
<tr>
<td>Year 2</td>
<td>49.20% (15.33%)</td>
<td>0.36 (0.21)</td>
<td>0.30 (0.17)</td>
</tr>
<tr>
<td>Year 3</td>
<td>33.80% (13.93%)</td>
<td>0.41 (0.18)</td>
<td>0.40 (0.19)</td>
</tr>
</tbody>
</table>

Note. Note linking connections included building-on, rising-above, and referencing.
Table 4

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

<table>
<thead>
<tr>
<th></th>
<th>Total cliques</th>
<th>Average size of cliques</th>
<th>Mean Cohesion Index</th>
<th>Mean # of cliques each student belongs to</th>
<th>Mean # of cliques the teacher belongs to</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td></td>
<td>Mean (SD)</td>
<td></td>
</tr>
<tr>
<td>Year 1</td>
<td>6</td>
<td>4.67 (0.52)</td>
<td>10.83 (7.21)</td>
<td>1.05 (0.21)</td>
<td>5</td>
</tr>
<tr>
<td>Year 2</td>
<td>25</td>
<td>6.00 (0.70)</td>
<td>2.68 (1.12)</td>
<td>5.68 (4.45)</td>
<td>25</td>
</tr>
<tr>
<td>Year 3</td>
<td>61</td>
<td>5.74 (1.08)</td>
<td>1.78 (0.36)</td>
<td>15.18 (11.48)</td>
<td>16</td>
</tr>
</tbody>
</table>

Note. 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 are.
Table 5

Freeman’s Graph Centralization Measures of Note Linking Networks across Three Years.

<table>
<thead>
<tr>
<th>Designs</th>
<th>In (receiving links)</th>
<th>Out (linking to others)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1: Fixed-groups</td>
<td>56.20%</td>
<td>56.20%</td>
</tr>
<tr>
<td>Year 2: Interacting-groups</td>
<td>53.10%</td>
<td>62.60%</td>
</tr>
<tr>
<td>Year 3: Opportunistic-collaboration</td>
<td>38.43%</td>
<td>33.68%</td>
</tr>
</tbody>
</table>

**Note.** The graph centralization measures were computed based on degrees of receiving and sending out note linking contacts.
### Table 6

Evaluation of Students’ Knowledge Advances Summarized in Their Portfolio Notes.

<table>
<thead>
<tr>
<th>Designs</th>
<th>Number of inquiry themes addressed</th>
<th>Depth of understanding $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Year 1: Fixed-groups</td>
<td>7.64 (2.11)</td>
<td>4.80 (0.94)</td>
</tr>
<tr>
<td>Year 2: Interacting-groups</td>
<td>9.82 (3.17)</td>
<td>5.21 (1.04)</td>
</tr>
<tr>
<td>Year 3: Opportunistic-collaboration</td>
<td>16.45 (2.69)</td>
<td>5.72 (0.70)</td>
</tr>
</tbody>
</table>

*Note: $^a$ 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 understanding was computed by multiplying these two ratings.*