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RESEARCH ARTICLE

Socio-cognitive dynamics of knowledge building in the work of 9- and 10-year-olds

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Abstract This study examines four months of online discourse of 22 Grade 4 students engaged in efforts to advance their understanding of optics. Their work is part of a school-wide knowledge building initiative, the essence of which is giving students collective responsibility for idea improvement. This goal is supported by software—Knowledge Forum—designed to provide a public and collaborative space for continual improvement of ideas. A new analytic tool—inquiry threads—was developed to analyze the discourse used by these students as they worked in this environment. Data analyses focus on four knowledge building principles: *idea improvement*; *real ideas, authentic problems* (involving concrete/empirical and abstract/conceptual artifacts); *community knowledge* (knowledge constructed for the benefit of the community as a whole); and *constructive use of authoritative sources*. Results indicate that these young students generated theories and explanation-seeking questions, designed experiments to produce real-world empirical data to support their theories, located and introduced expert resources, revised ideas, and responded to problems and ideas that emerged as community knowledge

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evolved. Advances were reflected in progress in refining ideas and evidence of growth of knowledge for the community as a whole. Design strategies and challenges for collective idea improvement are discussed.

Keywords Knowledge building · Deep understanding · Collective responsibility · Inquiry threads · Conceptual change

Knowledge-creating organizations emerge from a social process that engages participants "in complex, unpredictable interactions" (Sawyer, 2003, p. 19), with no single participant setting the agenda (Barab et al., 1999), and with goals emerging from interactions within a complex network of people and ideas (Valsiner & Veer, 2000). The need for knowledge creation pervades work in most fields, driving the need for education in which students are able to work with ideas creatively and productively.

Contemporary learning approaches depend on students to generate educationally productive questions to drive inquiry and deepen understanding (e.g., Brown & Campione, 1990; CTGV, 1996; Edelson, Gordin, & Pea, 1999; Gardner, 1999; Hmelo & Lin, 2000). Although inquiry is entering more and more classrooms, in practice students often solve pre-specified problems or gather information on specified topics (NRC, 2000; Rop, 2003; Zhang & Sun, 2005). Part of the problem is the difficulty elementary and middle school students have in formulating questions that guide inquiry in productive directions (Krajcik, Blumenfeld, Marx, Bass, & Fredricks, 1998). This problem is, of course, heightened by concerns with meeting curriculum standards and assessments, and the fact that student inquiry is typically limited to generating and answering personal questions.

Taking collective responsibility for the advancement of knowledge is the essence of knowledge building theory, pedagogy, and technology (Scardamalia, 2002, 2003; Scardamalia & Bereiter, 1994, 2003), and addresses the recognized need to engage students in self-directed, emergent inquiry (Chinn & Malhotra, 2002; Hannafin, Land, & Oliver, 1999; Lehrer, Schauble, & Petrosino, 2001; Roth & Bowen, 1995). In order to take over responsibility for idea improvement, students have to recognize that their own ideas, like ideas in general, can be continually improved. Collective responsibility implies responsibility beyond improvement of personal knowledge. For the group to take collective responsibility, ideas must have an "out-in-the-world" existence. They are not equivalent to personal beliefs or notions, but are more like the theories and inventions that have a public life in knowledge-based organizations and societies. They are a part of community knowledge, which is, roughly, the state of the art in a community. Toward this end students contribute their ideas to a communal knowledge space and share a commitment to improving ideas of value to their community.

Can young students take responsibility for charting the course of ever deepening understanding, and correspondingly "rise above" to more coherent explanations and higher-level conceptualizations, without pre-specified scripts and without an extensive amount of teacher direction? To address this question, the authors analyze the knowledge building discourse of a class of Grade 4 students, focusing on their performances in regard to four socio-cognitive dynamics of knowledge building.

Socio-cognitive dynamics of knowledge building

According to dialectical philosophers (e.g., Hegel, 1969), contradictions exist in reality, and the most appropriate way to understand the movement of that reality is to study the development of those contradictions. A knowledge building community is a social activity system that targets communal knowledge creation supported by collective and sustained idea improvement. This system requires rising above dualities or contradictions (Chen & Zhang, 1999; Zhang & Sun, 2005) as knowledge builders interact with diverse people and ideas and negotiate multiple perspectives to stay the course of idea improvement. Scardamalia (2002) has elaborated 12 knowledge building principles, forming a complex, interactive system of forces that drive this process. In this study we focus on the four principles most evident in the work under investigation: (a) *idea improvement*, advanced through monitoring what is known and what needs to be known; (b) *real ideas, authentic problems*, advanced through negotiating ideas arising from real-world, experiential, and experimental work and abstract, conceptual artifacts used to explicate and refine ideas and set forth new problems of understanding, (c) *community knowledge*, advanced through bridging what is of benefit for personal knowledge advancement and what will benefit the community as a whole; and (d) *constructive use of authoritative sources*, advanced through comparing and connecting ideas, models, explanations constructed by the local community and those represented in external or authoritative sources. These dynamics of knowledge building are elaborated below.

Idea improvement

This principle highlights the dynamic between what is known and what needs to be known. Awareness of what is known and what issues, problems, challenges and so forth lie beyond drives people to seek new information and generate new understanding. Advances lead to further problems or redefinition of existing problems at more abstract levels, thus continually enlarging the space of what needs to be known. This process is enhanced through supports in Knowledge Forum software, which was designed as a knowledge building environment (see Scardamalia, 2004). For example, customizable scaffolds are used to support high-level knowledge operations such as theory refinement. Students are encouraged to elaborate their mental models through the ‘‘my theory’’ scaffold support and their problems of understanding through the ‘‘I need to understand’’ scaffold support. Through elaborating what they know and need to know, they are engaged in a process of ever-deepening understanding. And through collaborative work in a public knowledge space, they help improve each other's ideas and "rise above," using a "rise above" function in Knowledge Forum, to new and improved theories, as superordinates of previsions work. Movement between what is known and needs to be known, in concert with going deep and rising above, defines a complex interactive system for idea improvement.

Real ideas, authentic problems

This principle highlights the interplay between concrete, empirical and abstract, conceptual artifacts. Work with a full range of epistemic artifacts (Scardamalia & Bereiter, 2006; Tweney, 2002) serves to advance understanding. It is popularly believed that objects that can be touched represent the "real world." The abstract and conceptual are less real and less available to young students. Yet the underlying idea behind "real ideas, authentic problems" is that student's ideas are as real as the objects they touch. Cognitive studies reveal the importance of coordinating empirical evidence with theoretical hypotheses during scientific discoveries (Klahr & Dunbar, 1988; Zhang, Chen, Sun, & Reid, 2004). Students' first-hand observations, experiments, and design experiences are important aspects of their scientific inquiry, which cannot rely solely on co-variations of observed events (Koslowski, 1996). But work with the empirical is not sufficient. Movement between the concrete/empirical and the abstract/conceptual drives idea improvement by engaging students in authentic problems of their own construction, not simply what curriculum designers consider authentic problems.

Community knowledge

The creation of community knowledge requires attention to what is of benefit for personal knowledge advancement as well as what will benefit the community as a whole. They work with the full set of ideas generated by the community, identifying weaknesses, engaging in constructive criticism, pursuing better explanations, and defining new problems. Through various forms of interaction with the ideas of peers, new and improved ideas are continually diffused throughout the communal knowledge space. This space is extensible, via the Internet, to the worldwide community of knowledge workers. Thus work between individuals and the community—work of benefit personally and collectively—is easily extensible to work between one community and multiple communities beyond the classroom. This fosters an inner–outer community dynamic that serves to further enhance knowledge advancement (Woodruff & Meyer, 1997).

Constructive use of authoritative sources

This principle addresses the dynamic process involving both local community resources and external or authoritative sources. The discourse in a local knowledge building community represents one part of the overall knowledge in a field—one part of the historically accumulated and ever expanding knowledge in society. It is unrealistic to expect every local community to make novel contributions to society's knowledge; what is important is that local discourse leads to understanding that are new to the local participants or superior to their previous understanding (Bereiter, 1994). The local community needs to take a receptive and critical stance to the ideas represented in their community, and also toward authoritative sources—books, experts, the teacher, and so forth. These sources should not serve as "end knowledge"—the ultimate state of understanding—and thus inhibit continual idea improvement (Scardamalia, 2002). Rather, authoritative sources serve to inform and produce further cycles of idea improvement (see also, Chernobilsky, DaCosta, & Hmelo-Silver, 2004).

In summary, socio-cognitive dynamics underlying knowledge building principles engage knowledge builders in knowledge spaces that they collectively create and improve. Participants take high-levels of responsibility for managing a process advanced through recording ideas in a public and collaborative space that then represents their idea diversity and the space of ideas to be continually improved. Through sustained and collaborative work they "rise above" to increasingly more coherent and sophisticated conceptualization. This process helps them negotiate the space of both personal and communal knowledge, of their personal theories and statements of what they need to know, of self-generated experiments and interpretive conceptual artifacts, and of their own ideas and resource material. Assuming collective responsibility for these activities differentiates the knowledge building approach from inquiry practices and project-based learning in which the teacher directs the work in a largely pre-determined way—defining inquiry tasks and sub-tasks, specifying phases and activities, grouping students, establishing a division-of-labor framework, defining resources, presentation formats, evaluation, and so forth (see also, Chinn & Malhotra, 2002).

In the present study, we analyze the extent to which Grade 4 students are able to assume high-level responsibility for their knowledge work, in the absence of pre-specified scripts and activities and without extensive teacher direction. Are these young students able to manage the socio-cognitive dynamics identified above? Is the result both communal and individual knowledge advancement? In line with the four dynamics identified above, specific questions, analyses, and expected outcomes of this study are summarized in Table 1.

Method

The knowledge building environment

In this study, the process of sustained and collaborative idea improvement was supported by Knowledge Forum, second-generation Computer-Supported Intentional Learning Environment (CSILE). The heart of CSILE/Knowledge

Table 1 Research questions and analyses

Dynamics	Specific questions	Analyses	Expected performances
Idea improvement	How do students identify and address questions over time, and how do they refine their ideas?	Categorize student questions, and trace the change of ideas in their discourse.	Students generate and address questions targeting deep explanations and core issues, and shift toward a more scientific view.
Real ideas, authentic problems	How do students incorporate real-world empirical data to support conceptual advancement?	Identify patterns of use of empirical data, and the effect of evidence on quality of ideas.	Students bring data from experiments, observations, and past experiences into the discourse, and show evidence of efforts to make sense of the data.
Community knowledge	Do contributions from individual students benefit the community as a whole? To what extent do ideas in the communal space spread and benefit the community as a whole?	Analyze frequency and nature of students' contributions to the work of other students. Compare the number of readers to writers of notes, and analyze knowledge gains related to the inquiry threads.	Students frequently respond to each other's ideas and questions in a way that supports conceptual advancement. Knowledge building discourse in each inquiry thread involves students as writers and readers, with knowledge gains attributable to reading, not just writing.
Constructive use of authoritative sources	What are the patterns of use of authoritative sources during knowledge building discourse?	Identify patterns of use of expert resources.	Students find relevant expert resources and introduce them into the community; more importantly they go beyond the given information to generate and improve their ideas.
Overall	Can individual students effectively gain new knowledge through emergent knowledge building? How are the four dynamics related to individual knowledge gains?	Pre- and post-test comparisons; analyses of students' portfolio notes. Correlation analyses.	A significant improvement of performance pre- to post-test; Students' portfolio notes report diverse ideas with high levels of scientificness and epistemic complexity. Significant correlations between indicators of the dynamics and quality of students' ideas summarized in portfolio notes.

Forum (see Scardamalia, 2004, for detailed descriptions) is a networked multimedia community knowledge space created by community members. By authoring *notes*,[1] participants contribute theories, working models, plans, evidence, data, reference material, and so forth, to *views*, which are workspaces for various clusters of inquiry, design, modeling or other forms or activity conducted by the community. Both notes and views are multimedia spaces, supporting text, graphics, and video. Supportive features for knowledge building discourse allow users to *co-author* notes, *build on* and *annotate* notes of community members, create *reference links* with citations to each other's notes, add *keywords*, and create *rise-above* notes to summarize, distill, and advance their discussions. Knowledge Forum also has "*scaffolds*" to aid the creation of epistemic artifacts. The theory-building scaffold, for example, encourages participants to enter, improve, and search ideas conforming to the following: "My theory," "I need to understand," "New information," "This theory cannot explain," "A better theory," and "Putting our knowledge together." Scaffolds are customizable, so teachers and students can tailor their scaffold supports to their curricular and subject matter needs. Activity (reading, writing, building on, referencing, etc) is recorded automatically. Analytic tools work as background operations so that patterns of contribution, revision, and interaction for each individual and for the class as a whole can be quickly assessed and fed back into the ongoing process.

Participants

Participants in the study were 22 students from a Grade 4 class at the Institute of Child Study, University of Toronto, and their teacher. The students, 11 girls and 11 boys, were introduced to knowledge building pedagogy and Knowledge Forum in Grade 3, and in that context they studied science (e.g., worms, plants) and geography. The Grade 4 teacher collaborated with researchers and had been using the knowledge building approach and Knowledge Forum for the previous two years. Judged from advances in approach and student results over this three-year period, the teacher was as committed to knowledge building for himself as for his students.

Knowledge building design and implementation

In the present study, the fourth-grade students studied optics for approximately four months, in line with principles and practices for knowledge building. Research from the previous year led students to wonder how worms sense light. In Grade 4, the teacher encouraged them, through face-to-face and online discussions, to elaborate what they needed to know about optics, to set forth their theories, to search for useful resources, and to design research to test and improve their ideas. He did not define tasks and activities in

[1] The italicized words in this section represent basic features of Knowledge Forum referred to throughout this article.

advance, but allowed students to define them, as they elaborated and refined their problems of understanding. In the teacher's own words: "We encourage a process of inquiry and ask 'why, why', and not to be content with a superficial understanding. We never want the children to feel they've got it, even in the way we form our notes—they say 'this is what I understand and if I could I would explore this further, or if I had support from other people I could do...."

In terms of classroom organization, the teacher developed increasingly effective means for having students take responsibility for their own knowledge advancement and for that of their peers. In the work reported in this study, he experimented with having the whole class collaborate opportunistically to understand optics and to progressively identify important, related issues (e.g., light sources, how light travels, colors, lenses and mirrors, vision). Knowledge Forum provided the public space in which their collective works were recorded, in views corresponding to these goals. This shared resource made this new approach possible. The views helped to keep the top-level goal center front and to keep the structure fluid: small groups formed and reformed based on evolving needs, and sub-goals were identified in related views that were linked and elaborated to enable the structure of the whole to proceed effectively. On a daily basis, students were free to explore any problem from any view in the database. They all took responsibility for the overall growth of the database.

In order to promote students' reflection on their progress, the teacher often initiated discussions about "what are our knowledge advances?" Following a discussion, students voluntarily formed into small groups, each adopting a view, for which they took responsibility. They read all the notes in the view, summarized the problems and knowledge advances, and recorded them in the background of the view. Figure 1 shows one view in the students' database focusing on issues of luminescence. The main knowledge advances were highlighted by the students. Near the end of inquiry, each student wrote a reflective portfolio note about what he/she knew about light in reference to the knowledge advances identified through online and offline interactions.

Overall, students generated problems of understanding, discussed diverse ideas/theories through whole class face-to-face knowledge building discourse, conducted self-generated experiments and observations, searched libraries and the Internet, and shared new resources through cooperative reading. Along with these offline activities, students shared their problems, ideas, data, and resources in their database. The teacher helped integrate online and offline discourse by referring to database notes during face-to-face discussions and encouraging students to record their questions, theories, and findings from face-to-face discourse in the database. He created a risk-free environment conducive to knowledge building: reading for deep understanding, engaging in inquiry and dialogue, providing resources and encouraging students to contribute theories as well as authoritative sources, and working along with students to bring interesting controversies to the fore. He developed a community culture in which elaborating intuitive conceptions and seeking deeper understanding were valued.

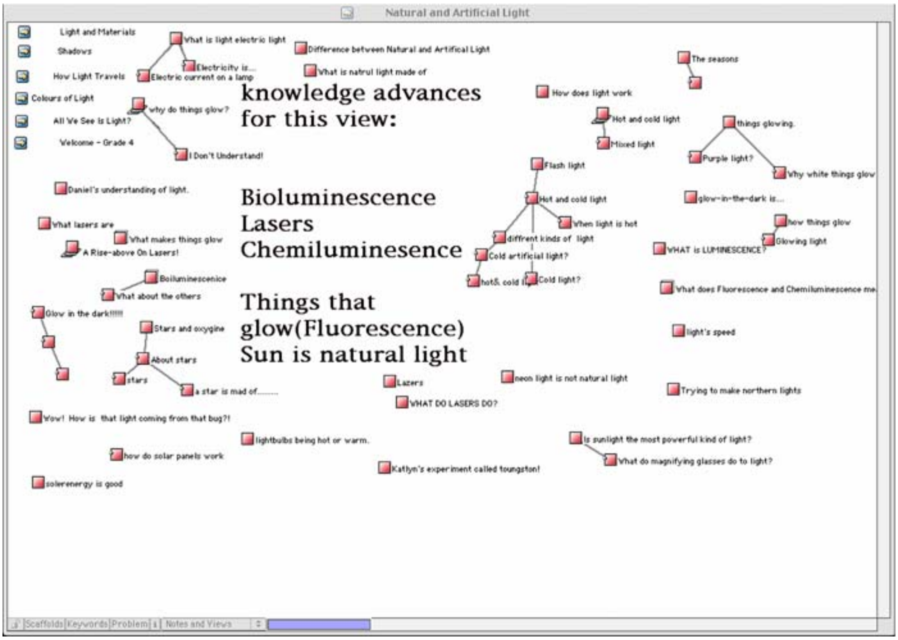

Fig. 1 Knowledge advances identified in the view of "Natural and Artificial Light." Each square icon represents a note. A line between two notes represents a build-on. Students recorded their major knowledge advances in the background of this view

Data analysis

The Knowledge Forum database was used as a window into student discourse and inquiry, aided by interviews with the teacher and a combination of quantitative and qualitative data analyses.

In computer-supported collaborative learning (CSCL) environments, one widely used method for assessing patterns of discourse is conversation thread—analysis of question–answer or opinion–comment exchanges (e.g., Hewitt & Teplovs, 1999; Howell-Richardson & Mellar, 1996). This method is valuable for understanding "what- and how- interactions," but often fails to connect conversation patterns with activities that have various conceptual intentions (see also, Lipponen, Rahikainen, & Hakkarainen, 2002). To map the socio-cognitive dynamics of knowledge building in a community, we need to understand what students, as a community, are trying to achieve, based on goals reflected in their discourse. To this end, we coded students' discourse in Knowledge Forum into distinct conceptual lines of inquiry—inquiry threads (Zhang, 2004). We regarded "inquiry threads" as "ethnographic chunks" (Jordan & Henderson, 1995) for the discourse analysis of knowledge building in the online environment. An inquiry thread can be defined as a series of notes that address a shared principal problem and constitute a conceptual stream in a community knowledge space. The defining feature of an inquiry thread is its principal problem, which is equivalent to "issue at hand" of an action episode in a situated activity (Barab, Hay, & Yamagata-Lynch, 2001). For example, in the current study, students wrote 27 notes in an extended discourse on the nature of rainbows, thus constituting an inquiry thread titled ‘‘Rainbows.’’ This inquiry thread involved a number of conversation threads (i.e., build-on structures or trees) that addressed the same principal problem.

The first author read and re-read all the notes in Knowledge Forum, and identified principal problems addressed by the community. As has been noted earlier, based on discussions of ‘‘what are our knowledge advances?’’ students identified the problems and knowledge advances in each view, and recorded them in the view’s background (see Fig. 1). The lists of knowledge advances identified by these ‘‘insiders’’ (community members) provided a guideline for the identification of problems in the communal knowledge space. Meanwhile, the coding process was also open to those inquiry focuses that had not been identified in the student-generated lists. Using the identified principal problems as the ‘‘tracers’’ (Roth, 1996), the rater clustered the notes that follow in the space of the same problem into one inquiry thread.

Over four months, the students created 287 notes in seven views (two unfinished notes were considered invalid for coding purposes). Within the communal knowledge space, 28 inquiry threads emerged. These inquiry threads are represented along a timescale in Fig. 2, starting with the first note created and ending with the last note created or modified. The numbers following the code and title of each thread indicate the number of notes, authors, and readers, respectively. For example, the inquiry thread of ‘‘shadows,’’ lasting from early February to mid-April, included 11 notes authored by 11 students seeking a deeper understanding of the nature of shadows, with all 22 students as readers. There were also occasions when more than one of the 28 main problems were addressed within the same note. These ‘‘bridging’’ notes ($n = 24$), which are highlighted with dots and lines in Fig. 2, reflect conceptual links among inquiry threads, interconnecting them within a network that grows with the knowledge building process. As we can see from the graph, there are many connections between the inquiry threads of rainbows and prisms; and types of materials, mirrors and reflection, diffuse reflection, and how light travels.

To gauge the reliability of inquiry threads analysis, two raters independently coded the notes ($n = 30$) in the view ‘‘Shadows.’’ They independently identified the principal problems (e.g., nature of shadows, sizes of shadows, eclipses, and sundials) addressed in this view (full agreement), and clustered the notes under these principal problems (inter-rater consistency = 83%).

The network of inquiry threads shown in Fig. 2 provided the framework for analysis of socio-cognitive dynamics. We coded students’ notes in each inquiry thread following the procedure of content analysis of verbal utterances defined by Chi (1997). The goal of this analysis was to understand the dynamics of knowledge building as represented in the following facets: *idea improvement* (question asking, driven by statements of ‘‘I need to understand’’; idea generation and improvement); *real ideas, authentic problems* (use

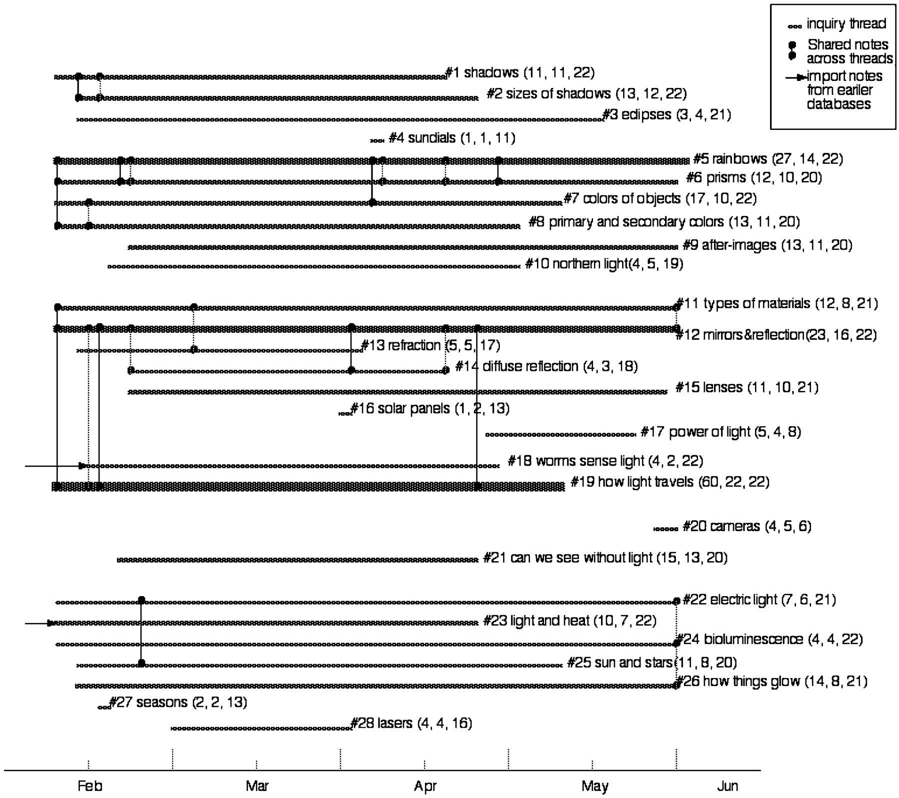

Fig. 2 Network of inquiry threads in Knowledge Forum. The numbers following the code and title of each thread indicate the number of notes, authors, and readers, respectively

of empirical data along with conceptual constructions); *community knowledge* (contributions to personal and collective spaces); and *constructive use of authoritative sources* (identifying authoritative sources along with ideas of one's own making). For the inquiry threads analysis, as indicated above, the first author read and re-read the notes to identify important categories in students' discourse with regards to the socio-cognitive dynamics. A coding scheme was developed based on this iterative process, and used to code each note (see Appendix A). Optics is a domain that involves a broad array of naïve conceptions (Galili & Hazan, 2000), and so notes were coded on a four-point scale (1—pre-scientific; 2—hybrid; 3—basically scientific; and 4—scientific) based on Galili and Hazan's (2000) facets-scheme framework for analyzing students' misconceptions in optics. This scale was used to rate learners' personal ideas stated in their notes. Using the same sample of notes in the view "Shadows," a second rater independently coded students' ideas resulting in an inter-rater reliability of .80 computed based on Pearson correlation.

To evaluate individual knowledge gains, we had students complete pre- and post-tests composed of 18 questions, which covered 10 of the 28 themes addressed by the inquire threads (e.g., shadows, mirrors and reflection, rainbows, etc), with a full score of 54. Due to the fact that the test was designed at the beginning of the unit, and did not cover all the themes that emerged during the inquiry, we additionally rated students' portfolio notes, which were written to summarize their knowledge advances about light and to provide a means to measure their personal knowledge gains. We divided each portfolio note into idea units—the smallest unit of text that conveyed a distinct idea regarding optics. Each idea was coded in terms of (a) inquiry thread/theme addressed, (b) level of scientificness (1—pre-scientific; 2—hybrid; 3—basically scientific; and 4—scientific), and (c) the level of epistemic complexity (1—unelaborated facts; 2—elaborated facts; 3—unelaborated explanations; and 4—elaborated explanations) (see Appendix B). The four-point scale for rating the epistemic complexity of ideas was adapted from Hakkarainen's (2003) scale for rating explanations. Two raters independently coded one student's portfolio note that included 36 idea units, resulting in an inter-rater consistency of .78. When coding an idea, the raters paid particular attention to its semantic context so that partition of ideas would not break up important semantic relations.

Results and discussion

Idea improvement

How did students identify and address questions over time?

Each of the 28 inquiry threads shown in Fig. 2 addressed a principal problem that emerged in the community discourse. Student 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 (thread #19), color vision (thread #9), colors of opaque objects (thread #7), concave and convex lenses (thread #15). This was true despite the fact that the students were not led by the teacher through pre-decided tasks or assignments to these concepts; rather, the process they collectively engaged in led them deeper into the conceptual domain, and new and more demanding concepts came to the fore as they conducted their research. For example, when researching the problem of how light travels (#19), the students first came up with the idea that light travels in a straight line. Later, by talking with his uncle who had a science background, a student picked up the concept of light wave, which he apparently recognized as something he and his classmates needed to understand. According to the Ontario Curriculum, understanding of "light wave" is expected for students in Grade 8. The apparent contrast between "straight line" and "wave" triggered a debate among the students. A conceptual advance was achieved when JD made a rise-above of these two perspectives by saying: "Putting our knowledge together, ... light travels in a straight line but it is a wave. Light is made up of the electromagnetic waves." This then became a new object of discussion.

In an inquiry thread, students indicate current problems and use the public space to invite peer input, and to generate potential solutions. Table 2 reports the number of notes (a) addressing factual problems, which are solved by finding out factual information; (b) addressing explanatory problems that are advanced by generating explanations about "why," "how," "what-if," and so on; (c) raising new factual problems for peers to address; (d) raising new explanatory problems for peers to address; and (e) contributing personal ideas and theories concerning the problem in a thread.

According to Hakkarainen (2003), successful knowledge building is characterized by the generation of explanatory questions. Young children often ask more factual than explanatory questions. In this study, however, students posted and addressed many more explanatory than factual problems (see Table 2). This reflects their self-directed efforts with the goal of deep rather than superficial understanding of the phenomena under investigation. At the same time, the proportion of explanatory problems differs across inquiry threads, depending on the nature of issues addressed. Problems that are more factual appeared in those threads that concerned factual issues. For example, students discussed what colors are primary and secondary in thread #8.

Table 2 Number of problems and ideas in inquiry threads

	Number of notes addressing factual problems	Number of notes addressing explanatory problems	Number of notes raising new factual problems	Number of notes raising new explanatory problems	Number of notes stating personal ideas
Total of the 28 threads	30	156	16	39	177
Mean (per thread)	1.14	6.14	0.64	1.50	6.93
SD	1.55	7.51	0.99	1.91	9.25
#1 shadows	0	11	0	0	8
#2 sizes of shadows	0	9	1	0	11
#5 rainbows	0	19	2	5	18
#6 prisms	2	5	2	1	8
#7 colors of opaque objects	1	6	0	3	13
#8 primary and secondary colors	5	3	3	1	8
#9 after-images	0	7	0	3	6
#11 types of materials	4	4	0	2	7
#12 mirrors and reflection	1	15	1	3	13
#15 lenses	0	8	0	0	8
#19 how light travels	1	35	2	7	47
# 21 can we see without light	0	15	0	1	14
#23 light and heat	3	1	3	2	4
#25 the sun and stars	2	2	0	4	7
#26 how things glow	1	8	0	5	4

Note: Inquiry threads defined as large included at least ten notes each

Progressive problem solving was evident in threads with a large number of notes (e.g., #2, #5, #7, #9, #12, #15, #19, #21, #26), in which students set forth their theories and what they needed to know, and addressed increasingly complex problems. For example, in the thread on rainbows (#5), students initially asked how rainbows are made, leading them to the understanding that the rain droplets split sunlight to make a rainbow. Based on this understanding, students generated further problems and statements of what they needed to know, such as: How can a big thing like a rainbow "be activated by mere raindrops"? (by SL) "There are lots of colors of the rainbows, why are they always in the same order"? (by KT) "Why do rainbows always take the shape of a semicircle"? (by SL).

To what extent did students change their understanding within their discourse space?

This study examines students' efforts for idea improvement from many perspectives, including the deepening inquiry threads, generation of deepening questions, social exchanges focusing on conceptual advancement, constructive use of empirical data and authoritative sources, and epistemic complexity of ideas in portfolio notes. In this section, we examine idea improvement in inquiry threads, rating students' personal ideas on the continuum from pre-scientific to scientific understanding, and traced change for each inquiry thread. We selected 15 large inquiry threads that included more than ten notes each. Altogether, these large threads had 184 notes, 162 of which contributed personal ideas and theories. Knowledge Forum allows users to modify their notes after creation. In the following analysis, we sequenced the notes in each of the 15 large inquiry threads according to the time of the last modification, and divided the notes in each thread into three stages with each stage having an equivalent proportion of notes. Table 3 presents the mean level of "fit with authoritative accounts" or scientificness, as assessed by independent ratings of students' ideas across the three stages of the large threads. An analysis of variance (one-way ANOVA) comparing the mean scientificness levels of ideas indicated a notable growth along the three stages ($F(2, 159) = 13.51$, $p < .001$, $\eta^2 = .15$). Post-hoc comparisons using the least significant difference (LSD) test showed significantly higher ratings for Stage 2 ($p < .01$, Cohen's $d = .59$) and 3 ($p < .001$, Cohen's $d = .98$) than Stage 1, and for Stage 3 than Stage 2 ($p < .05$, Cohen's $d = .42$). These results indicate that students changed their understanding of optics from a naïve view towards a more scientific view. For example, early notes in the rainbows thread (#5) explained that rainbows were the result of particular chemical materials floating in the sky after raining; while notes in the third stage noted the relations between rainbows and separation of white light.

The teacher engaged with students in their online work. He read notes, and along with students, identified conflicts or gaps in the knowledge of the community, and identified problems to stimulate deeper inquiry. He was

Table 3 Improvement of ideas across three stages for 15 large inquiry threads

	Stage 1	Stage 2	Stage 3
Mean	1.93	2.46	2.86
SD	.90	.90	.99
n	57	55	50

Note: The notes in each large inquiry thread were sequenced according to the time of the last modification, and divided into three stages with equivalent numbers of notes. Students' ideas in these notes were rated on a four-point scale (1—pre-scientific; 2—hybrid; 3—basically scientific; and 4—scientific)

engaged with students in knowledge building, thereby helping to model knowledge building practices. He wrote 19 notes, all build-ons to students' notes: 16 posed thought-provoking questions, with 14 of these asking for clarification, elaboration, and justification of ideas (e.g., "I thought worms do not have eyes, so then how do they sense light?" "What's your evidence for your theory that...?" "What do you mean by...?"). He used questions to deepen students' inquiry rather than set them on a new course of inquiry. This discourse structure differs dramatically from classic classroom discourse, which is initiated by a teacher's question, followed by a response from a student, and terminated by evaluative feedback from the teacher (Lemke, 1990; Mehan, 1979).

Overall, the above analyses suggest that in a supportive knowledge building environment, Grade 4 students were able to manage the dynamic between what they knew and what they needed to understand to advance their knowledge. They generated what we might term "knowledge building discourse." Many forms of discourse keep a conversation going; what is distinctive about the discourse of these students is it served to drive their inquiry deeper into the domain, and gradually advanced their understanding from a naïve towards a more scientific framework. They initiated the inquiry and then used processes parallel to those used by the teacher, rather than waiting for the teacher to guide their inquiry.

Real ideas, authentic problems

For the dynamic involving the interaction of the empirical and conceptual, we were interested in patterns of use of empirical data in relations to idea improvement. We analyzed students' uses of empirical data, including experimental results, observations, and experiences reported about phenomena under investigation in different inquiry threads. Altogether, there were 63 notes that reported empirical data, with 45 notes reporting findings from self-conducted experiments; and 18 reporting personal observations or life experiences. The students used the empirical data in one of two patterns. The first was description of experiments, observations, or experiences without elaboration of ideas (28 notes). For example, in the inquiry view on materials and light, YS reported what happened in an experiment, but without any explanations, conclusions, or implications: “When you put wax on a mirror, [s]hine a flash light on it then it will reflect darker and fainter.” A second pattern, representing an explanatory approach, was to use experiments or observations/experiences to justify ideas (35 notes). The descriptive approach might serve to highlight and thereby enrich specific experiences related to phenomena under investigation, but from a knowledge building perspective, the explanatory approach is more productive. It treats ideas as focal—as real as objects in the physical world—and uses data of specific events for the purpose of idea improvement. Young students often do not distinguish explanations from data, tending to view explanations as being embedded in data, not interpretations given to data (Carey & Smith, 1993; Kuhn, 1993). In the present study, students more frequently used an explanatory approach to justify and improve ideas, although a substantial number of notes remained in the database with no interpretation based on empirical data.

We were interested in whether empirical justifications help students advance their understanding. There were 35 notes with ideas that were empirically justified and had, on average, a scientificness rating of 2.66 ($SD = 1.11$). There were 142 notes presenting ideas with no empirical evidence and they had, in contrast, a mean level of scientificness of 2.30 ($SD = .99$). A t-test revealed a marginally significant effect slightly in favor of the strategy of empirical justification for achieving scientific understanding ($t = 1.85$, $df = 175$, $p = .066$). Further study needs to examine this effect to understand how to maximize the value of empirical data for idea improvement.

In this knowledge building community, experiments and empirical evidence were embedded in a scientific discursive, chain of inquiry process (Lehrer et al., 2001). Frequently, empirical data in a note became the object of further discussions, resulting in critical examinations and multiple interpretations of evidence. For example, in the discourse on vision, CO got an idea from a book indicating that people can only see with light. NTH raised an alternative idea supported by her life experience: “My theory is when you are in a dark room all you can see are the outlines of things. For example[,] while in a movie theater all you can see is the dark outline of that person. In response, NT interpreted NTH’s evidence from a different perspective: “[T]hat’s because the movie screen has light on it so you can SEE it!!!!!!”

Community knowledge

Did the work of individual students benefit the community as a whole?

In the online environment, community members contributed notes and read, built on, annotated, rose-above, and referenced each other’s notes. Student contributions to the work of others’ were categorized by the raters as either: (a) Making *conceptual* comments to develop other learners’ ideas, to state alternative ideas, to provide resource material or suggestions for inquiry, or to create rise-above notes based on other’s notes; or (b) Making *formal* comments concerned with discourse *per se*, including spelling, grammar, formats of presentations (e.g. using graphs), and uses of Knowledge Forum that would make entries more meaningful to other community members (e.g. clarify the problem, use scaffolds or keywords). Students made 103 conceptual comments: 40 were to develop peers' ideas (e.g., "That's true, I think that..."; "Here are some examples of..."), 27 expressed alternative ideas (e.g., "I disagree, because..."), 19 were questions for their peers (e.g., "What about...?"; "What's your evidence?"), 15 were rise-above notes that summarized the group's understandings and tried to achieve new insights (e.g., "Our theory is that light travels in microscopic waves..."), four provided related expert resources, and three gave suggestions for further inquiry (e.g., "Can you think of a way to test your theory?").[2]

They made 55 formal comments (e.g., "You missed the word..." "Please use keywords."), which were all in the form of annotations, embedded in the note rather than a build-on to it. The fact that these were annotations reflects an awareness, on the part of these young students, of the important and appropriate difference between input to individuals (personal annotations within a note directed specifically to the author) and input to serve community needs (build-ons to notes that are meant to advance understanding for the community as a whole). Overall, data showed a high frequency of responses to each other's ideas and questions in the community knowledge space, most of which concentrated on conceptual advancements and at creating a knowledge space of value to both individuals and the community as a whole.

To what extent did ideas in the communal space spread and benefit the community as a whole?

In a context where students have diverse and distributed expertise, there arises the question of how ideas spread (Brown et al., 1993). Our assumption is that the more a note is read the greater the opportunities for knowledge diffusion. Therefore, to examine idea spread, we analyzed students' participation in different inquiry threads as writers (contributors) and as readers and also considered the average percentage of notes read by each student. The average number of readers of an inquiry thread (M = 18.07, SD = 4.48) was far greater than average number of writers (M = 7.52, SD = 4.92) (F (1, 27) = 159.57, $p < .001$, $\eta^2 = .86$). As was noted earlier, each inquiry thread addressed a shared problem of understanding. After a problem/issue was raised by a subset of students in the community space, that problem was taken up by other students, with a growing number of students as writers and even more as readers. In this way ideas are brought to the attention of a wide network of community members. In this community, students engaged in the inquiry themes through opportunistic interactions, as the teacher opted for flexible rather than fixed group interactions. As we can see from Fig. 2, inquiry threads that addressed more central issues of the domain tended to involve more students as writers and readers. For example, 11 important

[2] A comment might be scored in more than one category.

inquiry threads, including shadows, sizes of shadows, rainbows, prisms, colors of objects, primary and secondary colors, after-images (color vision), mirrors and reflection, lenses, how light travels, and can we see without light, each engaged at least ten students as writers, and almost all the students as readers. Through the emergent process of collaboration, students devoted more effort to more significant lines of inquiry, increasing the chance of knowledge advancement and diffusion in those fields.

Our next analysis of idea spread was designed to determine if knowledge advances made by a few students were later taken up by other classmates. To this end, we compared the number of students contributing to an inquiry thread as writers to the number of students who reported knowledge gains about the theme of that inquiry thread in their personal portfolio notes. For example, one student wrote in his portfolio note: ‘‘The umbra is the darkest part of the shadow.’’ This was coded as a knowledge gain about inquiry thread #1: Shadows. An ANOVA revealed a significant difference between the average number of students who contributed to the discourse of an inquiry thread ($M = 7.52$, $SD = 4.92$) and that of students reporting knowledge gains concerning that thread in their portfolio notes ($M = 12.48$, $SD = 8.84$) ($F(1, 27) = 10.99$, $p < .01$, $\eta^2 = .29$), indicating that knowledge advances reported by students spread to a wider network of community members.

The analyses of note reading and personal knowledge gains reported by students provide evidence of idea spread in this community. A further question concerns the link between reading patterns and knowledge gains: Is it true that the more readers, the wider spread of ideas as evaluated by students' reported knowledge gains? A correlation analysis was performed to examine the relationship between the number of readers involved in an inquiry thread and number of students reporting knowledge gains concerning that inquiry theme. A significant correlation (Pearson $r = .49$, $p < .01$) was observed indicating a moderately strong link between these two variables. By reading notes in a community space, a student could increase his/her personal knowledge about inquiry themes of the whole community, including those not investigated personally.

The problem of knowledge diffusion has also been investigated by Roth (1996). He observed diffusion of three types of knowledge in a Grade 4–5 classroom conducting hands-on projects: facts, tool-related practices (using glue guns in construction tasks), and concept-related practices (adoption of triangular braces). Concept-related practice was found to be relatively slow in diffusion as gauged by the number of students using the concepts in project work. A reason suggested for slow diffusion of concepts was that students' were focused on the production of material artifacts; concepts were not essential. Roth suggested that teachers expend much effort convincing individuals to attend to the ideas behind activities. In the current study, with students at the same age, we observed ‘‘diffusion’’ of conceptual knowledge as readily as work with material artifacts. This outcome seems to be attributable to the fact that the teacher supported students in the use of a public, easily accessible space to pursue and improve their theories. He also focused his efforts on enabling fluid, self-organizing collaboration and interactions that focused on the interaction of material and conceptual artifacts and collective idea generation and improvement. This focus on a tightly interwoven integration of the material and conceptual, along with collective idea improvement, distinguishes a knowledge building community and the use knowledge building environments to support it.

Constructive use of authoritative sources

A knowledge building community needs to make constructive use of authoritative resources. To understand how these students used authoritative sources, raters identified notes that referred to reading material, the Internet, and experts or other adults (e.g., the teacher, a design researcher, parents). A total of 66 notes were categorized as including expert sources identified by students from multiple sources, and many in advance of sources that would be expected to be used at the elementary school level. For example, in an effort to figure out the reason for afterimages, four students found and cooperatively read an article "Colors and Cones" in a book titled "Optics." In a co-authored note, they summarized what they had learned from this article, and introduced the concepts of color wheel and opposite colors and the property of eye cones sensitive to light of different colors. Similarly, in the inquiry thread on how light travels, CLJ introduced the experiment of Thomas Young showing the wave property of light.

Two patterns emerged from these notes incorporating expert resources: (a) *Introducing resources*: students find and introduce to others expert resources by summarizing, providing an excerpt, or paraphrasing relevant information; and (b) *Going beyond resource material*: students not only introduce expert resources to others, but go beyond to generate ideas based on them. Both uses of resource material are helpful to the community, but going beyond leads to deeper understanding. Of the 66 notes that included resources, 40 introduced resources; 26 additionally involved idea generation based on the resource. Introducing resources is more frequent than idea generation based on the use of resources. Perhaps students introduced resources in one note and followed up in another, but that would not show up in our analysis.

The facilitative role of expert resources in knowledge building can be seen in the following examples: descriptions of after-images (thread #9) stirred curiosity and deepened inquiry; reading of material on light waves (thread #19), color spectrum (thread #13), lenses (thread #15), and luminescence (thread #14) directed students to deeper issues of the domain; and uses of "transparent," "opaque," and "translucent" in thread #11 helped students conceptualize ideas. The resources the students entered into the discourse stalled the discourse, or brought a line of inquiry to an end, on several occasions. For example, when debating how light travels, CO, who was a very active knowledge builder in this community, wrote:

> My theory is that light travels in waves because almost where ever you look for how light travels it will almost always say that light travels in waves. ... [I]t's almost impossible to make an experiment that proves it but I think that it was proved a long time ago that light travels in waves and a lot of people already know that!

The fact that light travels in waves was assumed to require no more research or inquiry. ''Constructive uses of authoritative sources'' is one of the determinants of knowledge building (Scardamalia, 2002). In fostering a knowledge building community, it is important to strike a balance between ''personal'' and ''authoritative'' perspectives. To promote students' constructive uses of expert resources, teachers encourage students to pose their own theories and to elaborate their ideas in advance of consulting expert resources, especially when they are new to knowledge building. Later, when they have a clearer understanding of the important role of their own ideas, it is easier to understand the importance of these ideas in relation to authoritative resources to improve ideas.

Students' knowledge gains and relation to the four dynamics

Individual knowledge gains

We analyzed individual knowledge gains based on pre-post test achievement scores. Students scored significantly higher on the post-test ($M = 43.21$, $SD = 3.75$) than they did on the pre-test ($M = 24.42$, $SD = 4.11$) ($F(1, 18) = 261.82$, $p < .001$, $\eta^2 = .94$). Unfortunately, no control class was available for comparison.

We further evaluated students' knowledge gains with respect to the theme of each inquiry thread based on their portfolio notes. As noted earlier, each portfolio note was divided into idea units. Students' knowledge gains were judged on the basis of number of idea units, and level of scientificness of ideas (1—pre-scientific; 2—hybrid; 3—basically scientific; and 4—scientific), and epistemic complexity (1—unelaborated facts; 2—elaborated facts; 3—unelaborated explanations; and 4—elaborated explanations) (see Appendix B). Epistemic complexity was considered important, because it measures students' effort 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). On average, each student's portfolio note included 33.05 ($SD = 7.02$) idea units, covering 16.45 ($SD = 2.69$) of the 28 inquiry threads,[3] with an average level of scientificness of 2.96 ($SD = .16$) and an average level of epistemic complexity of 2.05 ($SD = .27$). This outcome suggests that students developed basically scientific understanding about a wide range of core issues in the domain, including topics that are projected for

[3] Students tended to exclude inquiry themes at the periphery of their inquiries from their portfolio notes, for example, worms sense light, seasons, power of light (can light move small stuffs?), electric light, the sun and stars, etc.

Grade 8 in The Ontario Curriculum (e.g., light waves, colors of opaque objects, color vision, lenses). In term of epistemic complexity, a majority of students' ideas in their portfolio notes were elaborated facts. The level of epistemic complexity varies across inquiry threads. Ideas reported about more explanatory inquiry threads (e.g., how light travels, how solar panels work, light and vision, colors of opaque objects, and eclipse) were dominated by theoretical explanations, either elaborated or not. Moving students' ideas toward higher epistemic levels is central to knowledge building pedagogy.

Relationship between community dynamics and individual knowledge gains

We conducted correlation analyses to investigate the relationship between dynamics of knowledge building and the quantity and quality of ideas summarized in individual portfolio notes (see Table 4).

As Table 4 shows, inquiry threads with more contributors and more authoritative sources were associated with more knowledge gains based on an analysis of idea units in student-generated portfolio notes. The scientificness score for these idea units was correlated with the frequency with which authoritative resources were introduced in inquiry threads. The epistemic complexity of students' ideas, as reported in their portfolio notes, tended to increase when an inquiry thread engaged more contributors, involved more explanatory as opposed to factual problems, more empirical evidence to justify ideas, and more efforts for going beyond authoritative sources. Among these three variables (i.e., number of idea units, scientificness, epistemic complexity), epistemic complexity of ideas has the strongest positive relation with community dynamics of knowledge building.

Conclusions and implications

Can young students take collective responsibility for their own knowledge advancement? In this study, we analyzed the online knowledge building discourse of students in a Grade 4, knowledge building community, in an effort to answer that question. Analyses focused on socio-cognitive dynamics of knowledge building reflected in inquiry threads and portfolio notes in their online discourse in Knowledge Forum. As results indicate, these fourth graders raised authentic problems—problems of understanding resulting from their monitoring of the world around them and their attempts to explain various phenomena they were curious about. Most of their problems reflected a need for deepening their understanding and explanations, pushing forward various lines of inquiry that took them deeper into the domain. Students' knowledge building discourse showed explorations and explanations of a wide variety of phenomena—including those indicated in curriculum guidelines as appropriate for older students (e.g., light waves, interaction of light with opaque objects of different colors, color vision). Each student contributed notes, to multiple and appropriate inquiry threads, identifying their personal

Table 4 Pearson correlations: community dynamics and personal knowledge gains in inquiry threads

Knowledge gains relevant to inquiry threads, reported in portfolio notes	Knowledge building indicators in the inquiry threads						
	# of notes addressing factual problems	# of notes addressing explanatory problems	# of writers involved	# of conceptual comments	# of notes using evidence	# of notes introducing resources	# of notes going beyond resources
# of ideas	.21	.23	.42**	.23	.23	.39**	.02
Scientificness of ideas	–.18	.24	.31	.12	.20	.41**	.17
Epistemic level	–.43**	.45**	.39**	.27	.45**	.21	.34*

Note: The measures of personal knowledge gains included (a) number of ideas reported in portfolio notes concerning each theme; (b) level of scientificness of the ideas gauged on a four-point scale (1—pre-scientific; 2—hybrid; 3—basically scientific; and 4—scientific); and (c) level of epistemic complexity of the ideas (1—unelaborated facts; 2—elaborated facts; 3—unelaborated explanations; and 4—elaborated explanations)

*p < .10, **p < .05, ***p < .01 (2-tailed)

problems of understanding and posing insightful questions, reporting self-generated experiments, observations, empirical findings, authoritative sources, and, in many cases, presenting evidence for their ideas. Through these contributions, as well as reading and building on the notes of peers, they helped advance the community discourse.

The pre- post-test results showed significant advances for individual students, although control data were not available. Fortunately, ratings of "*scientificness*" of students' ideas in inquiry threads and in students' individual portfolio notes suggest that they moved from intuitive understandings of optics to more scientific accounts. Overall, the results support our assertion that young students can engage in sustained efforts aimed at deep understanding, and that public and collaborative work can help advance community knowledge. The pattern of results for this Grade 4 team working in the field of optics also suggests that young children can take collective responsibility for sustained improvement of community knowledge.

In parallel to the analyses of student participation, this study highlighted the teacher's role in facilitating a knowledge building community. The teacher took seriously the idea of collective responsibility for community knowledge, both in his design of classroom organization and in his own personal practices. Most notable, perhaps, are his contributions to knowledge building pedagogy, in his role as a knowledge building teacher. He deliberately experimented with new designs to promote collective knowledge advancement in his classes. A recent study traced his improvement over three years. He moved from use of fixed, small-groups to a dynamic, opportunistic collaboration approach, leading to ever increasing levels of knowledge advances and collective responsibility as evaluated using social network analysis and other measures of student knowledge advancement (Zhang, Scardamalia, Reeve, & Messina, 2006).

Analysis of conversation threads, a widely used method in CSCL research, focuses on question–answer and idea–comment exchanges (e.g., build-on trees). The analysis of inquiry threads in this study, in contrast, organized online discourses into conceptual streams broader than build-on trees. It proved particularly useful for profiling the diverse conceptual content that emerged during open-ended inquiry, and allowed us to uncover knowledge building dynamics. It provided an overview of individual participation in different strands of inquiry as well as the knowledge building goals of the community, and allowed us to trace the evolution of understanding over the full course of student work. Teachers who have seen the inquiry threads analysis have suggested that it could provide a means for students and teachers to monitor their community knowledge building advances, to indicate promising inquiry themes that stop prematurely or that are otherwise not evident, and to promote greater interaction between participants. To turn this method into a practical tool, we are designing a software program to automate networks of inquiry threads. The present study was aided by student-generated lists of knowledge advances. Further research is needed to determine the reliability and validity of this method in general CSCL contexts.

The results of the present study point to challenges that future research must address: (a) increase problem complexity and epistemic level, without sacrificing attention to scientificness; (b) strike a balance between specialization and communal knowledge advancement; (c) use authoritative sources to advance but not inhibit risk-taking in idea generation and refinement; and (d) increase the use of empirical data to examine and improve ideas.

Unfortunately, videos of face-to-face classroom discourse were not available, so we had no way to study the face-to-face discourse that surrounded and in many ways facilitated online discourse. Understanding the relationship between online and offline discourse is necessary to provide a clearer account of knowledge building. And of course, another limitation of the current study follows from the fact that this analysis was restricted to one teacher's class. Fortunately, there are a number of detailed accounts of knowledge building discourse in different schools and different classrooms (e.g., Bereiter, Scardamalia, Cassells, & Hewitt, 1997; Hewitt, 1996). Subsequent research will extend inquiry threads analyses to a broader range of teachers.

An important goal of our annual Knowledge Building Summer Institute is to demonstrate that knowledge building is extendable to a wide variety of contexts. An overview of presentations—see http://ikit.org/summerinstitutes.html—provides indication of the range of sites involved, including at-risk populations, with a history of low-literacy levels, as well as university, health care, and business contexts. As we have argued elsewhere, the greatest obstacle to the scalability and extensibility of knowledge building communities is the provision of suitable contexts and believing that students can take collective responsibility for their knowledge advances.

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Appendix

Appendix A Coding framework for content analysis of discourse in each inquiry thread

Categories	Sub-categories and defining features	Examples
Problems (addressed or proposed)	*Factual:* Questions to be answered with factual information (who, where, when, how many, etc.).	*What is translucent, transparent and opaque? Can light bounce off a chalkboard?*
	Explanatory: Questions satisfactorily answered with an explanation (why, how, what-if, etc.).	*How do solar panels work? Why do shadows exist? What happens when colored light goes in to water?*
Scientificness of ideas (4-point scale)	1. *Pre-scientific:* Misconceptions based on naive conceptual framework (scheme).	*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.	A student built onto the above note used as an example of pre-scientific ideas and made an improvement: *"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 ...*
Comment	*Conceptual:* Elaborates one or more relevant concept.	e.g., developing others' ideas, stating alternative ideas, providing further resources or inquiry suggestions, making rise-aboves, etc.
	Formal: Identifies an issue relevant to the discourse in Knowledge Forum.	e.g., spelling, grammar, graphs, scaffolds, keywords, etc..
Empirical data	*Experiments:* Reports results of self-identified experiments.	*My theory is that light travels in waves because when we did an experiment with projectors and a tennis ball hanging from the ceiling on a piece of string. And when we shone light on it the tennis balls' shadow was clear. But the strings shadow had some light on it, proving that some light got behind the string. This happened because light travels in waves.*

Appendix A continued

Categories	Sub-categories and defining features	Examples
	Observations or past experiences: Notes and reports relevant phenomena; recalls life experiences.	*My theory is that light travels in a wave lines because if you drive behind a bus you'll see heat that look in a wave.*
Expert resources	*Introduce new information:* Rephrases or summarizes information from readings, the Internet, or teacher, parent, etc.	*[New information] Shadow = a darkness made when light shines on to a opaque (nontransparent) thing. ... A small light source makes a dark shadow called a umbra. A large light source makes a small umbra and a lighter shadow called a Penumbra.*
	Go beyond given information: Uses expert resources to aid/advance personal ideas and understandings.	*My theory is that light travels in waves because almost where ever you look for how light travels it will almost always say that light travels in waves also my book said that light waves are shorter than ULTRA VOILET WAVES...*

Appendix B Coding scheme for ideas stated in the portfolio notes

Categories	Sub-categories and defining features	Examples
Inquiry thread/portfolio correspondence	An idea unit in a student's portfolio indicated knowledge gained from an inquiry thread.	The following idea in the student's portfolio was related to an idea in thread #1 (shadows): *"The umbra is the darkest part of the shadow."*
Scientificness of ideas	See Appendix A for the four-point scale.	
Epistemic complexity of ideas	*Unelaborated facts:* Description of terms, phenomena, or experiences without elaboration.	*The umbra is the darkest part of the shadow.*
	Elaborated facts: Elaboration of terms, phenomena, or experiences.	*The angle of incidents equals the angle of reflection, which 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.*

Appendix B continued

Categories	Sub-categories and defining features	Examples
	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.*
	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.*

References

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.

Barab, S. A., Hay, K. E., & Yamagata-Lynch, L. C. (2001). Constructing networks of action-relevant episodes: An in situ research methodology. *Journal of the Learning Sciences, 10* (1&2), 63–112.

Bereiter, C. (1994). Implications of postmodernism for science, or, science as progressive discourse. *Educational Psychologist, 29*(1), 3–12.

Bereiter, C., Scardamalia, M., Cassells, C., & Hewitt, J. (1997). Postmodernism, knowledge building, and elementary science. *Elementary School Journal, 97*(4), 329–340.

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

Brown, A. L., & Campione, J. C. (1990). Communities of learning and thinking, or a context by any other name. *Human Development, 21*, 108–126.

Carey, S., & Smith, C. (1993). On understanding the nature of scientific knowledge. *Educational Psychologist, 28*(3), 235–251.

Chen, Q., & Zhang, J. (1999). Use ICT to support constructive learning. In D. M. Watson, & T. Downes (Eds.), *Communications and networking in education* (pp. 231–241). Boston, MA: Kluwer Academic Publishers.

Chernobilsky, E., DaCosta, M. C., & Hmelo-Silver, C. E. (2004). Learning to talk the educational psychology talk through a problem-based course. *Instructional Science, 32*(4), 319–356.

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.

CTGV (Cognition and Technology Group at Vanderbilt). (1996). Anchored instruction and situated cognition revisited. In H. McLellan (Ed.), *Situated learning perspectives* (pp. 123–154). Englewood Cliff, NJ: Educational Technology Publications.

Edelson, D. C., Gordin, D. N., & Pea, R. D. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences, 8*, 391–450.

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

Gardner, H. (1999). *The disciplined mind*. New York: Simon & Schuster.
Hakkarainen, K. (2003). Progressive inquiry in a computer-supported biology class. *Journal of Research in Science Teaching, 40*(10), 1072–1088.
Hannafin, M. J., Land, S., & Oliver, K. M. (1999). Open learning environments: Foundations, methods, and models. In C. Reigeluth (Ed.), *Instructional design theories and models* (pp. 115–140). Mahwah, NJ: Lawrence Erlbaum Associates.
Hegel, G. W. F. (1969). *The science of logic* (A.V. Miller Trans.). London: Allen and Unwin.
Hewitt, J. G. (1996). *Progress toward a knowledge building community*. Unpublished doctoral thesis of the University of Toronto.
Hewitt, J., & Teplovs, C. (1999). An analysis of growth of patterns in computer conferencing threads. In C. Hoadley (Ed.), *Proceedings of CSCL'99: The third international conference on computer support for collaborative learning* (pp. 232–241). Mahwah, NJ: Erlbaum.
Hmelo, C. E., & Lin, X. (2000). Becoming self-directed learners. In D. Evensen, & C. E. Hmelo (Eds.), *Problem-based learning* (pp. 227–250). Mahwah, NJ: Erlbaum.
Howell-Richardson, C., & Mellar, H. (1996). A methodology for the analysis of patterns of participation within computer mediated communication courses. *Instructional Science, 24*, 47–69.
Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *Journal of the Learning Sciences, 4*, 39–103.
Klahr, D., & Dunbar, K. (1988). Dual space search during scientific reasoning. *Cognitive Science, 12*, 1–48.
Koslowski, B. (1996). *Theory and evidence: The development of scientific reasoning*. Cambridge, MA: MIT Press.
Krajcik, J., Blumenfeld, P. C., Marx, R. W., Bass, K. M., & Fredricks, J. (1998). Inquiry in project-based science classrooms. *Journal of the Learning Sciences, 7*(3/4), 313–350.
Kuhn, D. (1993). Science as argument: Implications for teaching and learning scientific thinking. *Science Education, 77*(3), 319–337.
Lehrer, R., Schauble, L., & Petrosino, A. J. (2001). Reconsidering the role of experiment in science education. In K. Crowley, C. D. Schunn, & T. Okada. (Eds.), *Designing for science* (pp. 251–278). Mahwah NJ: Erlbaum.
Lemke, J. L. (1990). *Talking science: Language, learning, and values*. Norwood, NJ: Ablex Publishing Corporation.
Lipponen, L., Rahikainen, M., & Hakkarainen, K. (2002). Effective participation and discourse through a computer network: Investigating elementary students' computer supported interaction. *Journal of Educational Computing Research, 27*(4), 355–384.
Mehan, H. (1979). *Learning lessons*. Cambridge, MA: Harvard University Press.
National Research Council (NRC). (2000). *Inquiry and the national science education standards: A guide for teaching and learning*. Washington, DC: National Academy Press.
Rop, C. J. (2003). Spontaneous inquiry questions in high school chemistry classrooms. *International Journal of Science Education, 25*(1) 13–33.
Roth, W. M. (1996). Knowledge diffusion in a grade 4–5 classroom during a unit of civil engineering. *Cognition and Instruction, 14*, 170–220.
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. (2003). Emergence in creativity, development. In K. Sawyer, V. John-Steiner, S. Moran, S. Sternberg, D. H. Feldman, J. Wakamura, & M. Csikszetmihalyi (Eds.), *Creativity and development* (pp. 12–60). Oxford, UK: Oxford University Press.
Scardamalia, M. (2002). Collective cognitive responsibility for the advancement of knowledge. In B. Smith (Ed.), *Liberal education in a knowledge society* (pp. 67–98). Chicago, IL: Open Court.
Scardamalia, M. (2003). Knowledge building environments: Extending the limits of the possible in education and knowledge work. In A. DiStefano, K. E. Rudestam, & R. Silverman (Eds.), *Encyclopedia of distributed learning* (pp. 269–272). Thousand Oaks, CA: Sage Publications.

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, Inc.

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

Scardamalia, M., & Bereiter, C. (2003). Knowledge building. In *Encyclopedia of education* (2nd ed., pp. 1370–1373). New York, NY: Macmillan Reference.

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

Tweney, R. D. (2002). Epistemic artifacts: Michael Faraday's search for the optical effects of gold. In L. Magnani & N. J. Nersessian (Eds.), *Model-based reasoning: Science, technology, values*. New York, NY: Kluwer Academic.

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

Woodruff, E., & Meyer, K. (1997) Explanations from intra and inter group discourse: Children building knowledge in the science classroom. *Research in Science Education, 27*(1), 25–39.

Zhang, J. (2004). 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.

Zhang, J., Chen, Q., Sun, Y., & Reid, D. J. (2004). A triple scheme of learning support design for scientific discovery learning based on computer simulation: Experimental research. *Journal of Computer Assisted Learning, 20*(4), 269–282.

Zhang, J., Scardamalia, M., Reeve, R., & Messina, R. (2006). Collective cognitive responsibility in knowledge building communities. *Paper presented at the Annual Meeting of American Educational Research Association*, San Francisco, CA.

Zhang, J., & Sun, Y. (2005). *Constructive learning*. Shanghai, China: Shanghai Education Publishing House.

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