Can Collaborative Knowledge Building Promote Both Scientific Processes and Science Achievement?

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Can Collaborative Knowledge Building Promote Both Scientific Processes and Science Achievement?

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Abstract

This study investigated the role of collective knowledge building in promoting scientific inquiry and achievements among Hong Kong high-school chemistry students. The participants included 34 Grade 10 (15-16 years old) students who engaged in collective inquiry and progressive discourse, using Knowledge Forum®, a computer-supported collaborative learning environment. A comparison class of 35 students also participated in the study. The instructional design, premised on knowledge-building principles including epistemic agency, improvable ideas and community knowledge, consisted of several components: developing a collaborative classroom culture, engaging in problem-centered inquiry, deepening the knowledge-building discourse, and aligning assessment with collective learning. Quantitative findings show that the students in the knowledge-building classroom outperformed the comparison students in scientific understanding with sustained effects in public examination. Analyses of knowledge-building dynamics indicate that the students showed deeper engagement and inquiry over time. Students' collaboration and inquiry on Knowledge Forum significantly predicted their scientific understanding, over and above the effects of their prior science achievement. Qualitative analyses suggest how student's knowledge-creation discourse, involving explanatory inquiry, constructive use of information and theory revision, can scaffold scientific understanding.

Keywords: knowledge building, scientific inquiry, collaboration, technology-mediated learning.

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¿Puede la construcción colaborativa del conocimiento promover los procesos científicos y el rendimiento en ciencias?

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Resumen

Este estudio investigó el rol de la construcción colectiva del conocimiento en la promoción de la indagación científica y de los resultados entre estudiantes de química de instituto de Hong Kong. Las y los participantes fueron 34 estudiantes del décimo curso (15-16 años) que participaron en indagación colectiva y discurso progresivo, utilizando el Foro del Conocimiento®, un entorno de aprendizaje basado en el ordenador. Una clase de comparación de 35 estudiantes también participaron en el estudio. El diseño instruccional, bajo las premisas de principios de construcción del conocimiento incluyendo la agencia epistémica, ideas improbables y conocimiento comunitario, consistieron de muchos componentes: el desarrollo de una cultural de aula colaborativa, participación en la investigación centrada en problemas, profundización en el discurso constructor de conocimiento y alienar la evaluación con el aprendizaje colectivo. Los resultados cuantitativos muestran que las y los estudiantes en el aula de construcción de conocimiento rindieron por encima de las y los estudiantes del grupo comparativo en la comprensión científica con efectos sostenidos en la evaluación pública. Los análisis de la dinámica de construcción de conocimiento indican que las y los estudiantes mostraron una implicación e indagación más profundas a lo largo del tiempo. La colaboración e indagación de los y las estudiantes en el Foro del Conocimiento predijeron de forma significativa la comprensión científica de las y los estudiantes, por encima de los efectos de su previo rendimiento en ciencias. Los análisis cualitativos sugieren que el discurso de creación del conocimiento de las y los estudiantes, que incluye indagación explicativa, revisión de la teoría y uso constructivo de la información, puede andamiar la comprensión científica.

Palabras clave: creación de conocimiento, indagación científica, colaboración, aprendizaje mediado por la tecnología

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It is now widely accepted that students need to work together to engage in collaborative inquiry and scientific discourse, and to develop the practice of scientists when they are involved in learning science (Scott, Asoko & Leach, 2007). Despite much enthusiasm, science learning is often reduced to surface forms of constructivist learning, with students busily engaged in gathering information from the web and completing predetermined tasks (Scardamalia & Bereiter, 2006); scientific inquiry is often limited to sequences of activities and fixed standards that focus on isolated skills rather than authentic inquiry (Chinn & Malhotra, 2002). The real goal of science for the creation of knowledge remains to be investigated, along with how knowledge-creation can be integrated with school curricula and assessment in classrooms.

Although it is widely recognized that students need to engage in discourse in science learning, less attention has been paid to how the learning environment can be designed to foster scientific understanding mediated by collective discursive practice and in particular, how it can address multiple goals of scientific inquiry, and discourse practice and school science. The possibilities for developing scientific inquiry mediated by technology merit investigation; at the same time, there is also a need to examine how students can learn the science concepts required by school curricula while working as communities of scientists to create new knowledge and improve their scientific practice. This study reports on an approach that is based on knowledge building, mediated by a computer-supported collaborative learning environment called Knowledge Forum® that focuses on students working collaboratively as members of a scientific community advancing the frontiers of their knowledge.

A major research strand regarding collaborative learning is the use of computer-supported collaborative learning (CSCL) environments (Stahl, Koschmann, & Suthers, 2006). An influential example of an educational model using CSCL technology is “knowledge building”, also known as knowledge creation, which is defined as “the production of knowledge that adds value to the community” (Bereiter & Scardamalia, 2010; Scardamalia & Bereiter, 2006). This model of knowledge building postulates that knowledge advancement is the collective work of a community, analogous to scientific communities, and that knowledge is improvable through discourse (Bereiter, 2002; Scardamalia & Bereiter, 2006). Knowledge building has been characterized as “knowledge creation”, a third metaphor for learning (Paavola, Lipponen, & Hakkarainen, 2004) that integrates the “knowledge-acquisition” (cognitive) and “participation” (situated) learning metaphors (Sfard, 1998). While knowledge building is now an increasingly popular term in the education literature, this model goes beyond students sharing and co-constructing joint understanding, often in group settings; it emphasizes “collective cognitive responsibility” and collective practices of the community to advance the community knowledge.

Knowledge Forum™ (see www.knowledgeforum.com), consisting of a multimedia database, constructed by students themselves, was designed to support collective knowledge advances and progressive discourse (Scardamalia & Bereiter, 1994; 2006). In knowledge-building communities, students make progress not only in improving their personal knowledge, but also in developing collective knowledge through progressive inquiry. When learning science in a knowledge-building classroom, students use Knowledge Forum to pose cutting-edge problems, generate theories and conjectures, search for scientific information, elaborate on the ideas of others, and co-construct explanations, thereby collectively revising and refining their ideas.

Learning science is difficult because students often have to tackle information that is different from or contradictory to what they believe. Many students experience conceptual difficulties in understanding the various levels (macroscopic, microscopic and symbolic) of scientific knowledge, and develop alternative conceptions in the complex process of learning (Treagust, Chittleborough & Mamiala, 2003). Research has placed increased emphasis on student agency and epistemology; research into intentional conceptual change, for example, postulates that such changes need to be regulated and controlled by students (Sinatra & Pintrich, 2003). This study proposes that knowledge-building pedagogy that emphasizes students’ epistemic agency and social metacognition will foster their scientific understanding, because when they collaborate to build knowledge, they have opportunities to reflect on their beliefs and understanding by comparing the beliefs and models of others with their own. Conflictual views can be identified and resolved collaboratively when students are working as a community of inquirers.

Further, when knowledge is constructed through discourse among student participants, students may understand better that knowledge is not handed down by authority, and will have opportunities to reflect on the nature of science and sources of knowledge.

Various studies have investigated the knowledge-building dynamics of how knowledge building can support scientific understanding and knowledge creation (see review, Chan, 2012; Caswell & Bielaczyc, 2001; van Aalst & Truong, 2011). Oshima, Scardamalia and Bereiter (1996) investigated differences among students with high- and low-conceptual progress and identified the importance of problem-centred knowledge. Hakkarainen (2004) analyzed the written productions of young students in physics posted onto a CSILE database (*Computer-Supported Intentional Learning Environment, the earlier version of Knowledge Forum*). These young students engaged in epistemological inquiry and pursued explanation-driven inquiry with some moving toward theoretical scientific explanation. Van Aalst and Chan (2007) examined how students' collective assessment and meta-discourse using knowledge-building portfolios can scaffold their conceptual understanding in high-school science. Zhang, Scardamalia, Reeve and Messina (2009) examined the socio-cognitive dynamics of knowledge building by investigating the collective cognitive responsibility of fourth-grade students in advancing their science knowledge.

Although there has been major progress in research on knowledge building, there is still a need for stronger empirical evidence to support the role of collective knowledge building in students' scientific understanding. In comparison with other inquiry models, knowledge building emphasizes the complex dynamics of scientific inquiry and there may be concerns that science content in school curricula may be neglected. In particular, since this model of knowledge building emphasizes collective and community advances, it is useful to examine whether it has educational benefits for individual students and how knowledge-building dynamics may contribute to the effects. While many studies in the knowledge building literature have been conducted among elementary school students, this study examined high-school students learning chemistry in Hong Kong classrooms, with a comparison group, to investigate how the knowledge-building approach and discourse affect students' scientific understanding. Teachers and educators may also be interested to see whether the increasingly popular inquiry-based approach to learning science, in this case knowledge building, has an effect on standardized tests and assessments used in public examinations. As the knowledge-building model is implemented increasingly in different countries, it would also be of interest to examine how the approach works with students in different cultural settings, and in particular in educational contexts that emphasize teacher-centered approaches and examinations.

Accordingly, this study investigated knowledge building and scientific understanding among a group of Grade 10 students (aged 15-16 years) studying chemistry in a high-school classroom in Hong Kong. The research questions are: (1) Do students involved in knowledge building perform better on chemistry assessment tasks based on the school curricula than do their peers? (2) How do knowledge-building activities predict students' scientific understanding? and (3) How do students engage in knowledge-building discourse and how might it foster their scientific understanding?

Methods

Participants

The participants were thirty-four students in a knowledge-building class and another thirty-five students in a comparison class attending a Grade 10 (15-16 years old) chemistry course at a Hong Kong Catholic girls' school. Students had a high-average ability and English was the medium of instruction in their classrooms. The students studied using English and wrote on Knowledge Forum in English. The comparison class studied the same chemistry curriculum during class; after school, while the knowledge-building students wrote on the forum, the comparison class worked on text-book exercises. Students in both classes had similar academic achievements and were taught by the same teacher.

The Classroom Setting

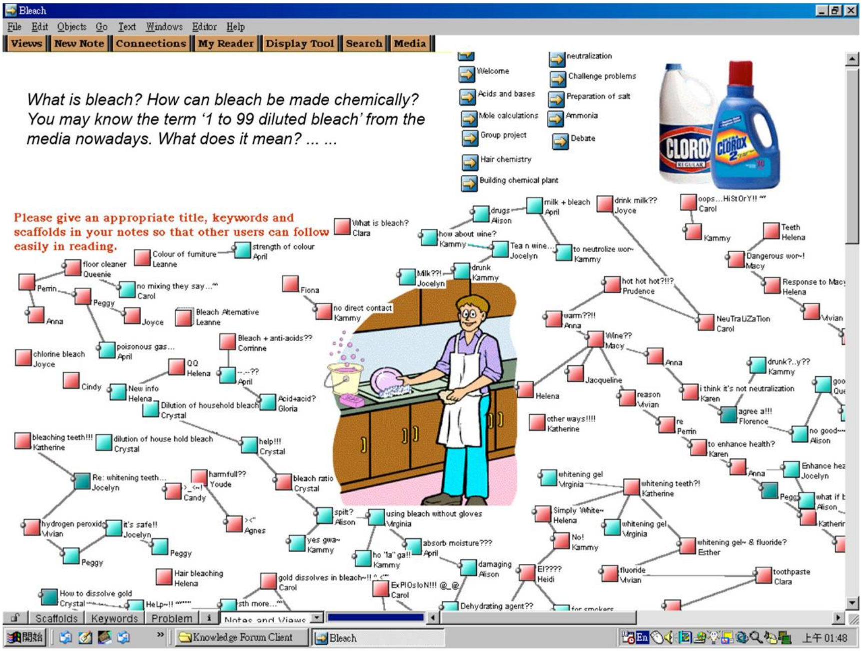
Both classes were taught using the chemistry curriculum determined by the Education Bureau (Ministry of Education) in Hong Kong. The teacher designed the learning environment, integrating the school curriculum with knowledge-building pedagogy. Primarily, the goal was to engage students to interconnect abstract concepts in chemistry on the macroscopic, microscopic, and symbolic levels. The study lasted several months (Jan-August) and had three periods: *Phase 1:* Initial Use of Knowledge Forum (Jan-Feb); *Phase 2:* Full Use of Knowledge Forum (March-April); and *Phase 3:* Use of Knowledge Forum after School Examinations in the Summer (July-August). Usually schoolwork finishes at the end of the academic year, which is followed by the summer holidays. In this study, the knowledge-building class continued to work beyond the end of term and into the summer months. They continued their collaborative inquiry, mediated by Knowledge Forum, despite the absence of the teacher.

Principle-Based Instructional Design

The design of the knowledge-building environment was premised on a set of interrelated knowledge-building principles (Scardamalia, 2002), and several key principles, including epistemic agency, improvable ideas, constructive use of authoritative information, and community knowledge, that inform the classroom design. “Epistemic agency” is a principle that focuses on having students take high-level agency charting their own inquiry; the principle of “improvable ideas’ focuses on students viewing ideas as objects of inquiry that can be improved continually; “constructive use of authoritative information” emphasizes students using new information as resources to refine their theories; and “community knowledge’ focuses on collective inquiry and advances in collective knowledge. While there were different classroom activities, the design emphasized developing a knowledge-building culture with students taking collective cognitive responsibility. Based on other studies conducted in Hong Kong classrooms, different components were included (Chan, 2008; Lee et al., 2006) and described as follows:

Development of a collaborative classroom culture. Before the implementation of Knowledge Forum, all of the students were provided with learning experiences to help create a collaborative knowledge-building culture. Classroom activities such as jigsaws, collaborative concept mapping and group-based scientific inquiry experiments may be commonplace now in science classrooms; in this study, the focus was placed on helping students to put their ideas to the forefront, and these ideas are public artefacts that can now be open to inquiry and improvement through students' collective efforts. Students own their problems and inquiry with *epistemic agency* and they work for collective advances in *community knowledge*. Through these principles and design activities, the students began to acculturate to the knowledge-building practice of asking productive questions, putting forth theories for revision and solving complex problems. They also activated their prior knowledge and articulated the abstract and particulate nature of chemistry concepts.

Collaborative problem-centered inquiry. The teacher worked with the students and designed the Knowledge Forum views to promote knowledge building and aligned *authentic problems* with the school curriculum (e.g., acids and bases, neutralization) (Figure 1). Several views (discussion areas) were created, based on scientific or everyday issues (e.g. the nature of 2-in-1 shampoo), and the students engaged in inquiry into authentic problems. Knowledge Forum supported epistemic agency and metacognition by having the students work with scaffolds (metacognitive prompts, e.g., "I need to understand", "My theory"). A key principle was that the students viewed *ideas as improvable* as they generated questions, posed alternative theories and hypotheses, brought in new information, considered different students' views, and collectively advanced their community knowledge. Problems emerging from the computer discourse were discussed in class, and several emergent problems, such as the chemistry of bleach and antiseptic alcohol, were formulated by the students. These ideas were integrated with their prior knowledge of chemistry concepts and were aligned with the topics in the chemistry curriculum.



What is bleach? How can bleach be made chemically? You may know the term '1 to 99 diluted bleach' from the media nowadays. What does it mean? ... ...

Please give an appropriate title, keywords and scaffolds in your notes so that other users can follow easily in reading.

Figure 1. A view on Knowledge Forum illustrating students' collective inquiry.

Rise-above and deepening the knowledge building discourse. As the unit continued, there were many more notes in the database but the discussion could be fragmented and scattered. Knowledge Forum designs support higher-level themes (theories) emerging from diverse ideas as students pursue idea improvement and deepening of the discourse. Over time, the teacher worked with the students to identify sub-themes, note clusters, and questions that needed further inquiry and revision. Note clusters were moved into rise-above views to help focus and extend the collective inquiry. Primarily, students worked collectively to deepen their inquiry through examining productive ideas and inquiries, scaffolding emergent discussions and theory refinement. Online and offline discourse worked together as students engaged in meta-discourse in knowledge-building classroom talks.

Concurrent and transformative assessment. Rather than focusing on teacher-led assessment, this principle emphasizes assessment as concurrent, embedded and transformative for students' knowledge building. The students reflected on their work and assessed the knowledge-building discourse, noting high-points in their knowledge advances. Specifically, the students had to select and write a reflective summary of four notes to assess the knowledge advances they had made, guided by the knowledge-building principles. Such reflections helped to promote a metacognitive understanding of their own knowledge building process and were rated and attributed as part of the course assessment.

The knowledge-building and comparison students both studied the same curriculum during the semester. However, whereas the Knowledge-Building students wrote computer notes after class, the comparison class students were asked to work on textbook exercises and problems after class.

Measures

Forum participation. Student participation, interaction and collaboration on Knowledge Forum was assessed using server log information via the software program called the Analytic Toolkit (ATK) developed by the Knowledge Building Research Team at the University of Toronto (Burtis, 1998). The Analytic Toolkit provides a wide range of indices to show participation and collaboration in Knowledge Forum, and we reported several common ones used in the literature: (a) the number of “note contribution” (notes written); (b) the percentage of notes “read” that reflect community awareness; (c) the number of “scaffolds” as metacognitive prompts (e.g., *I need to understand, my theory, a better theory*); (d) the number of “note revisions” that reflect recursive processes; (e) the percentage of notes with “keywords” to help other members identify and access notes; (f) the percentage of notes “linked” that refer to notes that build onto and notes that make references to other notes. The ATK measures have been used in numerous classroom studies and have been validated in other knowledge-building research studies (Chan & Chan, 2011; van Aalst & Chan, 2007).

Question asking and epistemological inquiry. How questions are posed is an important indicator of epistemological inquiry, as it reflects how students view ideas as objects of inquiry in knowledge building

(Hakkarainen, 2004). In this study, we examined all of the questions in this chemistry database. Different levels of questions emerged, resulting in a five-point scale characterizing responses ranging from fact-finding questions to explanatory and scientific-inquiry based questions. The scale development was based on earlier work on knowledge building (Chan, Burtis, & Bereiter, 1997) and epistemological inquiry (Hakkarainen, 2004) and the rating of student questions on Knowledge Forum (Lee et al., 2006). Examples of different levels of questions are included in the descriptions that follow. In this study, a second rater scored 30% of the responses and the inter-rater reliability based on Pearson correlation was 0.71.

Level 1 - Simple questions. Questions at this level sought a single piece of information, usually of fact-finding types. These questions were usually of the simple “what” and “yes/no” questions: "What pH do sweets have?" (#102), "What is ammonium sulphate?" (#29).

Level 2 - Simple questions with personal non-scientific guesses. Questions at this level were similar to those in Level 1 but they included some personal presuppositions: "But is the damage as serious as using dye to dye your hair? I think lemon juice is not that strong as those dyes...." (#31).

Level 3 - General information-seeking questions. These questions sought general information about a topic, and were usually of the “how” and “what’ variety: "What happens if concentrated acids react with metal carbonates/hydrogen carbonates???" (#67).

Level 4 - Explanation-seeking questions. Questions at this level sought explanations about a problem:

> Many home computers use ink jet printers. The print head works by squirting minute droplets of ink at the paper. This ink must be liquid before squirting but must not smudge or rub off once on the paper.

> How do we explain ink jet printing involving neutralization? (#262)

Level 5 - Scientific conjecture or theory-seeking questions. Questions at this level identified areas of conflict and put forth some plausible conjectures. Some may also have been questions that identified conflicts between ideas, or between conjectures and events, or that had the potential to modify current views,

> A website said that "If you have swallowed some bleach, drink milk so as to counteract the effect of NaOCl in the body through neutralization." Does it work?? But milk is slightly acidic, will chlorine gas evolve in our stomach?? It seems very horrible! Actually is egg acidic? So is the same reason implied? (#82)

Scientific understanding. At the end of the semester, students from both the Knowledge Building and comparison classes were assessed by an examination in chemistry consisting of questions designed to probe their conceptual understanding of chemistry based on the school curriculum. The students had to apply knowledge and explain new phenomena. The examination consisted of both forced-choice questions and open-ended questions, related to the curriculum and for examining scientific understanding. The students were also asked some unfamiliar questions that required them to show a good understanding of relevant chemistry concepts. As an example, one question asked, “A student tested the pH of two aqueous solutions, hydrochloric acid and ethanoic acid. She found that both had a pH 4. She concluded that the two acids were equally concentrated and also equally strong. Do you agree? Explain your answer.” This question tested the students’ understanding of the concepts of strength (strong or weak) and concentration (dilute or concentrated) of the acids. We also examined the students’ public examination results as a delayed posttest to investigate whether working on knowledge building had affected their performance in science.

Results

We first examined the effects of the knowledge-building environment on the students' scientific understanding followed by analyses of how knowledge building dynamics may have contributed to their scientific understanding.

Effects of Knowledge Building on Scientific Understanding

An ANOVA showed no differences between the two classes in their prior achievement scores in Grade 9 chemistry. The mean scores for scientific understanding for the Knowledge Building class and the comparison class after the program were 80.6 (12.4) and 70.1 (13.3), respectively (SD in parentheses). An ANCOVA that controlled for prior chemistry achievement showed a significant difference in scientific understanding between the two classes, F (1, 67) = 18.73, $p<.01$, suggesting the knowledge-building students outperformed the comparison students.

We also examined the performance of the two classes in the public examinations taken one year later as a delayed posttest to investigate the effects on science achievements and to test whether the students' understanding was sustained. We translated the letter grades into numeric values (A=5, B=4, C=3, D=2, E=1) and the results show that the Knowledge Building class obtained an average score of 3.8 (1.1) in the public examinations, while the comparison class obtained an average score of 3.5 (1.3). Thus, although the two classes had similar achievements in chemistry when they started Form Four (Grade 10), the knowledge-building students had obtained significantly higher chemistry scores at the end of Form Four, and continued to perform better at the end of Form Five (Grade 11) in public examinations.

Student Contribution in Knowledge Forum and Changes Over Time

To investigate knowledge-building dynamics and their possible effects on scientific understanding and achievements, we examined the students' contribution to Knowledge Forum and how these changed over time. The results from the Analytic Toolkit showed that the overall degree of student participation in Knowledge Forum was high, with each student creating, on average, 40.6 (17.0) notes and reading 66% of all notes. The percentages of notes *linked* and notes with *keywords* were also high (77% and 74% respectively), suggesting a high degree of interaction in the Knowledge Forum discussions. Although there is no norm against which to make a direct evaluation, comparisons with student participation levels in other computer forum discussions (Lipponen et al., 2003) indicated that the students were participating actively in this knowledge-building community.

We examined changes in the students' participation over three periods of Phase 1, Phase 2, and Phase 3 (Table 1). A MANOVA showed significant differences in ATK indices across all three phases, suggesting change over time. Post-hoc tests showed significant differences in all ATK indices, indicating gains in participation and collaboration from Phase 1 to Phase 2. Between Phases 1 and 3, post-hoc tests also indicated significant gains in the number of notes created and the percentage of notes linked. Taken together, there was significant growth in ATK indices from Phase 1 to Phase 2, and various indices were higher in Phase 3 compared to Phase 1.

Table 1
Participation and Collaboration in Knowledge Forum Over Time

	Phase 1	Phase 2	Phase 3
# of notes written	3.7 (5.7)	26.0 (13.5)	10.9 (8.4)**
# of revision	0.5 (1.5)	2.7 (4.2)	2.1 (3.2)*
# of scaffolds	0.7 (1.2)	3.3 (5.5)	1.5 (3.7)*
# of problems	2.1 (3.1)	9.6 (6.4)	3.1 (3.5)**
% of notes read	43.2 (37.1)	72.6 (30.2)	42.8 (35.1)**
% of linked notes	30.8 (41.7)	77.5 (21.1)	58.2 (38.9)**
% with keywords	42.2 (47.3)	72.0 (15.3)	58.5 (40.7)**

Note: $^*p < .05$; $^{**}p < .01$.

Epistemological Inquiry and Changes over Time

We examined the frequency and quality of the questions posed over the three periods (Table 2). We classified the questions as high-level (Levels 4 and 5) or low-level (Levels 1, 2 and 3). The mean number of high-level questions posed per student was 0.6 in Phase 1, 3.8 in Phase 2 and 1.4 in Phase 3. Combining question quality and frequency generated an inquiry score; for example, a student who posed one Level 1 question, one Level 2 question, and two Level 3 questions would have an inquiry score of 2.25 (the total question value divided by the number of questions asked).

Table 2
Depth of Inquiry on Knowledge Forum Over Time

	Phase 1	Phase 2	Phase 3
# of Questions	1.5 (2.5)	9.6 (6.6)	3.0 (2.8)**
# of High-Level Questions	0.6 (0.9)	3.8 (2.9)	1.4 (1.7)**
Inquiry Scores	1.7 (2.0)	2.6 (0.8)	2.4 (1.8)*

Note: *$p < .05$; **$p < .01$.

A MANOVA showed significant differences for all inquiry measures across the three phases. Post-hoc tests indicated significant differences on all three measures between Phases 1 and 2 suggesting increased depth of inquiry. There were no differences in inquiry scores in Phases 2 and 3, which suggests that the students maintained their levels of inquiry over the summer. Taken together, the qualitative ratings of the questions (inquiry) showed a similar pattern with the quantitative indices of forum participation. There was a general growth trend, and the students maintained an interest in knowledge-building inquiry, working on Knowledge Forum by themselves even after their examinations.

Prediction of Knowledge Building Measures on Scientific Understanding

We conducted analyses to examine how students' knowledge-building engagement and inquiry might predict their scientific understanding. We first combined the six participation (ATK) scores using factor analysis. Two factor scores were generated; the first termed "Productivity" (notes written, notes read, revisions and scaffolds) explained 40% of the variance, and the second, termed "Collaboration" (notes linked, keywords), explained 22% of variance. "Productivity" included the indices that focused more on student participation, such as the number of notes written, revisions made, scaffold uses, and notes read. "Collaboration" focused on students interacting and collaborating with each other, such as linking to and referencing the notes of other classmates, or using keywords to make their notes more accessible in a search. These two indices have been identified in other studies on knowledge building (e.g., Lee et al., 2006).

We found significant correlations among various measures, specifically that scientific understanding was correlated with prior science achievement based on the Grade 9 exam results (r = .67, p<.001) and ATK collaboration (r =.61, p<.001). A hierarchical multiple regression analysis on scientific understanding was conducted with prior science achievement (Grade 9 scores) entered first, followed by ATK collaboration scores, and then the inquiry scores (Table 3). The results showed that prior science achievement contributed significantly to scientific understanding (R^2= .45). When the ATK collaboration scores were entered, R^2 changed to .56 adding 11% of variance; when depth of inquiry scores was entered, R^2 changed to .63, adding an additional 6% of the variance. All changes were statistically significant. These findings suggest that, over and above prior science achievement, students' collaboration indices in Knowledge Forum and the quality of the questions they asked contributed significantly to scientific understanding. What is of particular interest is that it is not *productivity* but *collaboration* that contributes to scientific understanding.

Table 3
Multiple Regression of Prior Science Achievement, Collaboration (Analytic Toolkit), Depth of Inquiry on Scientific Understanding

	R	R^2	R^2 Change
Prior Science Achievement	.67	.45	.45***
ATK Collaboration	.75	.56	.11**
Depth of Inquiry	.79	.63	.065*

Note: *p < .05; **p < .01; ***p < .001.

Knowledge-Building Discourse and Processes

We provide an example based on student writing on Knowledge Forum to illustrate how knowledge building was manifested and how it might scaffold students' scientific understanding. This selection was based on the teacher's recollection of how he came to realize that it is possible for students to pursue problems collectively and engage in creating knowledge for the community. The example illustrates how students demonstrate epistemic agency, charting their own course of inquiry and viewing ideas as improvable and supported by constructive use of scientific information to refine their explanations.

The inquiry from which the excerpt was taken started with a question raised by Jacqueline, who wrote: "My mum has gone to the supermarket for[three] times… but still can't buy bleach [to kill the SARS virus]. Too many people want it nowadays… Can we use alcohol to kill the bacteria too?" She wanted to know whether alcohol has the same function as bleach in killing the SARS virus although she mistakenly used the term "bacteria" instead of "virus". This wonderment question sparked an inquiry into the relative properties of the two disinfectants and their effects on the SARS virus. The discourse continued with another student's observation about the strength of commercially sold alcohol.

She wrote: "The normal alcohol [sold on the market] contains 75% alcohol" (Cindy). This provided more information about household alcohol and led to further puzzlement: "Why is it 75%?" (Jacqueline).

A common theme is that students were engaged in posing problems and puzzlement. These two short exchanges helped the students to think more deeply about the effects of alcohol on bacteria and viruses and to question why only 75% alcohol, rather than pure alcohol, is used for sterilization. The puzzlement leading to a formulated problem brought about a search for new information; Jacqueline continued the explanatory discourse and wrote a paraphrased version of an explanation she found in a science book. She wrote:

> The concentration of pure alcohol is so high that it will, in no time… completely solidify the protein on the surface of the bacteria, so forming a layer of hard membrane. This layer prevents the alcohol from further diffusing into the bacteria… But the situation is different for alcohol mixed with water. The diluted alcohol will not quickly solidify the protein on the surface of the bacteria; it can diffuse into the bacteria and solidify all the protein content inside… That is why... diluted alcohol works better than pure alcohol in sterilization.

This explanation provided a plausible mechanism of how alcohol can kill bacteria at a microscopic level (by solidifying the protein of the bacteria) and why water is needed for proper disinfectant activity. However, the discourse did not stop there with this initial explanation. Other members of the community continued with the search for explanation that deepened the inquiry – Macy posed her puzzlement as follows:

> Mmm.... but then do you mean that the "protective protein layer" will block the bacteria from coming out? And [will] they be kept in our skin? Or even enter the body? Wow.... that's terrifying…But is the layer formed ON the bacteria... or somewhere else?

Macy was trying to clarify two related points pertaining to the explanation - where the “protective protein layer” is formed and what the consequences are of such a layer being formed. It can be seen that the students were posing queries and that they felt comfortable to write about their ‘uneasiness’ and what might not make sense to them. It is through such queries that the collective discourse can be deepened for idea improvement and *theory revision.* It is interesting to note that Macy did not refer to the book directly when she posed her questions, but rather to Jacqueline’s note: “do ***you*** mean that…”. It seems that, to Macy the authoritative information had become Jacqueline’s own ideas. The second point put the initial explanation to a more rigorous test by further considering the possible consequences that arose, thus opening the door for theory revision and “improvable” explanation.

The explanatory discourse went to a deeper level with another explanation given by Youde, which she had found in another science book. She paraphrased and wrote:

> Alcohol = ethanol (C_2H_5OH)… it has strong diffusing power. It can drill into the bacteria and denature its protein; and so kill the bacteria. In the past, people thought […followed by a few lines paraphrasing Jacqueline’s initial explanation]. But in fact, just pure alcohol or pure water cannot denature the bacteria’s protein. It is only with water and alcohol together that has the power… Protein is composed of long spiral chains... On the inside of the chains, there are many “base clusters” that dislike water. [On] the outside are many “base clusters” that like water. There exist attractive forces between these two different kinds of base clusters… These attractive forces have to be broken down first… Since the non-polar part of alcohol [molecules] is $–C_2H_5$, it can only destroy the attractive forces among the base clusters that dislike water…and water molecules can only destroy the attractive forces among the base clusters that like water…so water and alcohol need to work together in appropriate concentration..to sterilize.

As the students engaged in the pursuit of deepening inquiry, this new explanation not only refuted the old one but also brought out more chemical knowledge about alcohol *(Alcohol = ethanol* (C_2H_5OH)*)* and the structure of bacteria protein *(Protein is composed of...)* by giving more details at the microscopic level. The students' understanding of the original problem was revised and deepened continually, illustrating the characteristics of knowledge-building discourse and reflecting theory revision in science. Specifically, the problem on finding substitutes for bleach to kill bacteria (actually a virus) led successfully to a progressive scientific inquiry. It began with the wonderment question of whether alcohol can kill bacteria as bleach does. This puzzlement was formulated into a scientific problem: the role played by the concentration of alcohol in killing bacteria. These questions then led to an initial explanation aided by scientific information about how alcohol can kill bacteria (by solidifying the bacteria's protein); the original macroscopic question was examined at the microscopic level. The discourse continued to progress as the students viewed ideas as objects of inquiry for refinement, and the initial explanation was subject to query. New questions were raised and these puzzlements led to reformulation with a new explanation that elaborated on the microscopic structure of alcohol (with symbolic formula provided) and the protein of bacteria. Primarily the students worked collectively grappling with emergent problems and extending their knowledge.

Several discourse moves are manifested in this example, including the posing of wonderment questions, explanatory discourse, constructive use of information, and theory revision. Quite different from the knowledge transmission approach common in traditional Hong Kong classrooms, the students here took the emergent approach of intertwined questions and explanations in pursuit for idea improvement. Their discourse shows that the information was not viewed as something given from outside the community. On the contrary, they treated it as their public "property" or as an "object" that could be value-added or modified by any one of them (e.g., *"Do you [not the text] mean..."*). This suggests that the knowledge-building approach not only shaped the way in which the students went about their scientific inquiry, but also their epistemology of science. Most importantly, they were inquiring both to learn science content and also as scientists themselves formulating problems, posting initial ideas, revising their theories, and working at the cutting edge of the knowledge of the community.

Discussion

This study has investigated the role of collaborative knowledge building mediated by a computer-supported learning environment in fostering scientific understanding. Our results show that the knowledge-building students outperformed the comparison students on scientific understanding; student collaboration and inquiry scores in Knowledge Forum predicted scientific understanding over and above prior science achievement. The results also show several productive knowledge-building discourse moves, including wonderment questions, explanatory inquiry, constructive use of information, and theory revision that might help scaffold scientific understanding. Issues relating to the effects and roles of knowledge building in fostering scientific inquiry are discussed.

Whereas earlier studies in knowledge building have included evaluation designs with comparison groups (Scardamalia, Bereiter & Lamon, 1994), more recent studies have focused on elucidating the rich dynamics of knowledge building (see review, Chan, 2012). Since the knowledge-building approach emphasizes collective agency and emergent processes, there may be concerns that students, while engaged actively in knowledge-building inquiry processes, may not be learning adequate science content. One contribution of this study is that it provides additional evidence about the positive roles of collective knowledge building on scientific understanding and achievements, including a comparison group with delayed tests, thus enriching the knowledge-building literature. Specifically, our results show that the students who had experienced knowledge building outperformed the comparison students in school tests of scientific understanding and sustained their advantage in public examinations one year later. Furthermore, within-group comparisons using hierarchical regression analysis show that collaboration in Knowledge Forum and depth of inquiry were significant predictors of scientific understanding over and above the effects of prior science achievement. We have provided evidence that the students' active involvement in knowledge building did influence their science learning scores beyond prior science achievements.

It is interesting to note that the knowledge-building students obtained higher grades in *public examinations* than did the comparison students.

These findings suggest that student gains were not achieved at the expense of school learning. Rather, by deepening their understanding through explanation-based knowledge-building discourse, the Knowledge Forum students might have integrated their knowledge about chemistry better than did their counterparts in the comparison class. They made both individual and collective advances as they worked collectively and there were gains in both science concepts and authentic scientific practice. Such findings are important for developing knowledge-building innovations in different school contexts, and in particular those that emphasize standard curricula and examinations (Chan, 2011).

Although the quantitative findings provide general support for the positive effects of knowledge building on learning science, it is through examining the knowledge-building dynamics that a deeper understanding can be gained of how knowledge building scaffolds scientific understanding. Our findings show that the students' participation and inquiry improved over time, with them becoming increasingly engaged in their participation and collaboration in the forum. The participation indices were much higher than those reported in the literature for online discussions (Lipponen et al., 2003). In addition, the students engaged in deeper inquiry over time, moving from descriptive to explanatory questions. The level of questions asked has been shown to be important in scientific inquiry in cognitive research (Chan et al., 1997; Okada & Simon, 1997). Congruent with epistemological inquiry, idea improvement may be illustrated by moving scientific inquiry from the descriptive level to the question-driven explanatory level (Hakkarainen, 2004). The progress of the students in the Knowledge Forum discussions can be gauged in part by the level of their question-driven inquiry as represented by the questions they raised. Elaborating and building on peers' questions is important for science understanding in a developing knowledge-building community. The solving of real-life problems through collaborative problem-centered inquiry activates prior knowledge to enhance their problem-solving abilities in the context of chemistry.

The importance of question asking and explanatory inquiry has been well documented (Hakkarainen, 2004; Lee et al., 2006; Zhang et al., 2009), but we further show that collaboration in Knowledge Forum, as measured by the ATK collaboration index, contributes to science understanding over and above the effects of prior science achievement. Importantly, it was not the number of notes the students wrote or even how many thinking prompts (scaffolds) they used that made the difference. Rather, it was the extent to which they elaborated and built on their classmates' postings, questions and ideas that most enhanced their scientific understanding. Such empirical findings support theories of collaborative knowledge building -- they are consistent with the socio-cognitive dynamics emphasizing community connectedness (Zhang et al., 2009) and social dynamics (van Aalst, 2009) in knowledge-building communities. For classroom implications, it is important to encourage students to work collectively, building on, linking to, and referencing others' ideas rather than just working on their own ideas.

Qualitative analyses suggest that knowledge-building discourse may support conceptual, social and epistemic goals of science learning. In chemistry, the *conceptual* schema includes three levels of representations including macroscopic, microscopic and symbolic ones for explaining observed chemical phenomena (Treagust et al., 2003). Excerpts from the knowledge-building students' discourse suggest that collective problem formulation and co-construction help students to move from one level of representation to another while developing a deeper understanding of chemical explanations. We have also demonstrated that, when engaged in knowledge-building discourse, students had opportunities to articulate their views and to examine their own understanding with regard to others' models, thus helping them to develop metacognition and agency.

The knowledge-building approach to scientific inquiry focuses on students working *socially* and collectively as a community of inquirers, in which their goal is not only to improve their individual understanding of science, but also to view the ideas of the community as conceptual artifacts for improvement. In some ways, knowledge building may be closer to authentic scientific inquiry when this is understood to mean idea improvement and collective knowledge advances. The high-school students in this study were engaged in inquiry processes similar to those in *scientific and scholarly communities* – they were engaged in posing problems, forming conjectures and hypotheses, searching for information, and co-constructing explanations as they deepened their inquiry and refined their theories. The discourse analyses show how the students made progress in both scientific *concepts* and scientific *processes* of inquiry through working collaboratively, and emphasizing collective agency and progressive inquiry.

Excerpts from the discourse show how the students developed new ways of viewing the nature of knowledge. Information from science books is not information “out there”, but a resource for them to build and revise their theories. They might be developing an *epistemic* understanding about the nature of knowledge and the notion that ideas are improvable. During this process, the students might develop into active agents and knowledge builders. It is interesting to note that the students in this study continued their inquiry during the summer without the presence of the teacher. They may even have developed a different epistemological understanding, whereby they no longer saw the teacher as the sole source and authority of knowledge (Hofer & Pintrich, 2002), but could possibly see themselves and their peers as resources for learning and knowledge advancement.

Knowledge-building inquiry, as shown in this study, may help students to achieve multiple goals, allowing them simultaneously to develop an understanding of science concepts, to reconsider their views of science as evolving *(“In the past, people thought”)*, and to engage in the scientific practice by posing problems, constructing explanations and improving collective understanding. Knowledge building, through its primary focus on community knowledge growth, the scaffoldings provided by its principles and technology, and its focus on research- and explanatory-based inquiries into authentic problems, may help to address the persistent problems in science learning, namely difficulties in studying science, usually with an excessive focus on the symbolic level, the impoverishment of student metacognition, and students’ views of science as authoritative rather than evolving knowledge. As noted above, we conjecture that the students not only developed scientific understanding and inquiry skills, but also changed their views about learning and knowledge. However, these possible relationships among epistemological beliefs, knowledge building, and conceptual change need to be investigated further.

There are various limitations to this study that point to areas of further research. First, as in many technology-related studies that include multiple interacting factors, the comparison class was not a strong control, and thus the results should be interpreted with caution. The class curriculum was similar and the comparison students were asked to complete other work in the time the other students spent on Knowledge Forum after school. We included the comparison class to provide some background to our findings; it is noteworthy that intra-class regression analyses also revealed the benefits of Knowledge Forum participation and inquiry. Second, scientific understanding was examined primarily using school examination results. Although the paper included questions probing for qualitative understanding, and it has the advantage of assessing how collaborative inquiry-based learning such as the knowledge building model can be aligned with school science, more elaborate measures would be useful. Finally, further investigation should be undertaken to examine the roles of the teacher and classroom dynamics in fostering the growth of the knowledge-building community.

Conclusions

This study has shown how the design of a collaborative knowledge-building environment supports collaboration, inquiry and explanatory discourse in ways that facilitate both scientific processes and science achievement. We have provided additional empirical evidence to the knowledge-building literature, suggesting that collective knowledge building can have beneficial effects on school science learning. Such findings are important in light of increased emphasis on both curriculum standards and reformed approaches. As well, knowledge-building discourse, mediated by a computer-supported environment, addresses conceptual, epistemic, and social goals of science learning that allows students to develop a deeper understanding of science concepts, to reconsider their views of science, and to work together in a community to advance their knowledge frontiers. This study suggests that knowledge building can bridge “real science” and “school science” and can foster both “science learning” and “learning *about science”*, because of its emphasis on both the advancement of subject-matter understanding, together with epistemic beliefs, and scientific practice of theory building through a knowledge-building community. It also provides an example of how knowledge building can foster science learning in a cultural and educational context that places great emphasis on examinations. How knowledge building can be integrated in classroom practice in science education is the major question that requires further investigation.

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