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Fostering Students' Scientific Inquiry through Computer-Supported Collaborative Knowledge Building

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Abstract

The aim of this study was to investigate whether and how engaging with a computer-supported collaborative knowledge-building environment helps students to develop a more sophisticated approach to scientific inquiry. A total of 52 undergraduate students took a course entitled "Introduction to Natural Sciences" that was based on knowledge-building pedagogy. They were engaged in using the Knowledge Forum (KF) to conduct scientific inquiries and construct scientific concepts through online collaboration. We analyzed (1) the contents of students' online discussions and (2) students' online activity logs. Data were subjected to both qualitative and quantitative analysis. The results indicated that (1) after engaging in scientific inquiry using KF, the students were able to develop more sophisticated scientific concepts; and (2) while the quality of the students' scientific inquiries was overall correlated with the quantity of their online activities, it was found that not all types of knowledge-building activities contribute to effective scientific inquiry. Only when the focus of students' online activities is placed on sustained idea improvement can the quality of their inquiries actually be enhanced. We discuss possible ways of improving how students conduct online inquiries.

Keywords Scientific inquiry · Knowledge building · Computer-supported collaborative learning (CSCL)

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Introduction

Cultivating scientific literacy has always been an important research topic for science educators (American Association for the Advancement of Science 1993; Bybee 2015; National Research Council (NRC) 1996, 2000). Conducting scientific inquiries is considered an important way to develop science literacy (NRC 2000). Consequently, educators are always looking for better ways of incorporating scientific inquiry into science education. Reported pedagogical means to promote scientific inquiry range from highly structured (scripted) (for example, see Mehalik et al. 2008) to very open-ended approaches (for example, see Bell et al. 2005). Scripted inquiry is usually textbook-based, whereas open-ended inquiry tends to be student-driven and unguided. Previous studies have shown that scripted inquiry can help students learn more efficiently (Kussmaul et al. 2014; Sharples et al. 2015). Other studies have investigated how less-structured inquiry influences science learning (for example, see Bjønness and Kolstø 2015). Theoretically, engaging students in open-ended inquiry is more likely to promote students' autonomy, as this would be similar to how scientists work in the scientific community. Giving students opportunities to appreciate how scientists refine their theories over time should help them to understand not only the process of scientific inquiry but also the nature of science, thus further benefiting their science learning (PRIMAS 2011). Less-structured pedagogies such as project-based or problem-based learning have been adopted widely in science education, and have shown positive outcomes for students' understanding of the content as well as the nature of sciences, and for their skills (Allchin 2013). In these pedagogies, teachers act as facilitators or scaffolding providers (Hmelo-Silver 2004). Knowledge building, on the other hand, puts most of the responsibility on the students themselves, emphasizing student- and community-driven learning. Knowledge Forum, which was developed based on the knowledge-building principle, serves as the main scaffold. Although studies on the use of knowledge building have revealed positive influences on students' scientific learning (Chen and Hong 2016; Lee et al. 2011), few have tried to understand the mechanisms during students' online scientific inquiry process and their effects on students' scientific understanding. Hence, this study aims to create an open-ended inquiry environment, using a computer-supported knowledge-building environment called Knowledge Forum that has been successfully applied in various domains and cultural contexts over the past three decades (Chen and Hong 2016). The approach enables students to emulate how real scientists conduct scientific inquiries and develop theories. Consequently, the study examines how the elements of knowledge-building activities during such a process influence their learning outcomes.

Scientific Inquiry and Knowledge Building

Scientific inquiry can be viewed as the process of developing knowledge and gaining understanding of the natural world (NRC 2000). There are several elements to this process: defining problems, generating hypotheses, conducting investigations, analyzing evidence, formulating models, and evaluating results (White et al. 1999). Science curricula are generally designed to make extensive use of scientific inquiry since it has been shown to be highly beneficial in terms of enhancing students' understanding of science (Kremer et al. 2014; NRC 2000), increasing their interest and self-confidence (Akarsu 2012; Banerjee 2010), and developing students' critical thinking skills (Corlu and Corlu 2012). There is evidence that having an appreciation of how ideas are created, shared, and transformed can enhance students' understanding of science and scientific inquiry skills (Burgh and Nichols 2012; NRC 2000). It is therefore important to create a learning environment that facilitates the exchange of ideas and community knowledge building (Hong et al. 2015b). There are various approaches and formats to doing so, ranging from face-to-face to web-based, individualistic to collaborative, knowledge-based to idea-centered, curriculum- to theme-based, and highly structured to open-ended. We will first discuss the pros and cons of the different inquiry approaches to better understand how they influence students' science learning. Knowledge building, which served as the main instructional design principle for this study, will be further elaborated during the discussion.

In terms of the mode of inquiry, the most natural and common way to interact with people during inquiry is face-to-face (Duncan and Fiske 2015). In such an inquiry environment, teachers can observe directly how students react to the inquiry-learning tasks. Through students' body language, teachers can judge whether they are confused or disengaged during the inquiry, and make immediate adjustments to the learning activities. There is evidence that students prefer face-to-face inquiry learning because of the social or emotional support or the student-teacher interaction (Paechter and Maier 2010). However, there are temporal and physical constraints such as lack of equipment for conducting inquiry-based scientific learning in the classroom. To address these issues, web-based science inquiry learning is used to create a more flexible, more readily available alternative. Not only are students free of the restrictions of time and place, but they can also draw on resources from both the physical and digital worlds (Hwang et al. 2012). In addition, web-based inquiry also promotes students' technological literacy, provides them with chances to access and assess online resources as well as skills for referencing, searching, comparing, and identifying important science issues (Çalik et al. 2014; Kluge 2014). These activities enhance students' self-regulated learning (Paechter and Maier 2010). For example, Lee et al. (2011) reviewed 65 studies of web-based science learning published between 1995 and 2008. Their findings indicated that, although web-based science learning is not necessarily helpful for improving students' conceptual understanding, it was found that students' attitudes become more positive towards science and technology and that web-based science learning can promote students' cognitive skills and increase their motivation and engagement in science (Lee et al. 2011). In knowledge building, although there are face-to-face sections, inquiry activities on Knowledge Forum are considered as the main part of the learning as these activities allow students to conduct their inquiry flexibly. Students are more likely to keep their discussion active due to the boundlessness of the physical/virtual environments and time. In other words, they can conduct the inquiry whenever they want to.

In terms of the number of members involved in the inquiry, there are individual and collaborative inquiries. Individual inquiry is a form of self-directed learning in which individual students conduct inquiries according to their own interests and abilities (Chitkara et al. 2016; Li et al. 2010). Individual inquiry usually makes it easier for teachers to deal with the specific learning needs of each student (Wilen and McKenrick 1989), but the downside is the lack of social interaction. Given that communication and collaboration are recognized as important twenty-first-century skills (Trilling and Hood 1999) and that collaborative problem-solving ability is currently valued by educators (for example, the Programme for International Student Assessment, PISA), many studies have been devoted to facilitating collaborative inquiry. Learning through collaborative inquiry emphasizes the role of peers' facilitation, supported by teachers and social media (Hmelo-Silver 2004). Collaboration is common among the scientific communities. There is also empirical evidence that collaborative science learning improves learning processes, motivation, learning outcomes, and conceptual understanding (Bell et al. 2010). Knowledge building is a pedagogy that strongly emphasizes collaborative work. During the problem-solving process, students work collaboratively and continually to generate and improve the ideas that are of value to their class community (Scardamalia and Bereiter 2003). It goes beyond group learning as the forum is available for collaboration and joint work on ideas (Chen and Hong 2016). One of the knowledge-building principles, community knowledge, emphasizes the importance of all community members' co-constructing knowledge of value to the community. In addition, the principles of democratizing knowledge and symmetric knowledge advancement emphasize that the shared goal of the community is as important as individuals' learning goals (for details, see Scardamalia 2002). An individual contribution of ideas to the communal forum is viewed as enabling both the individual and the community to advance their knowledge.

In terms of the main purpose that drives the inquiry, knowledge-based inquiry is based on prepared teaching materials or textbooks. It allows students to systematically acquire rich knowledge of a topic. However, such knowledge is often viewed by students as authoritative truth. The process of inquiry sometimes becomes a process of verifying existing knowledge rather than advancing knowledge or understanding (Collins 1996). In contrast, idea-centered inquiry is a more flexible, self-directed process, based on constructing and revising self-generated scientific ideas (Hong 2011). Students can generate and continuously improve their ideas through discussion and argument with peers using evidence from various knowledge sources. This method may give students a better understanding of the theory that is the subject of their inquiry as well as helping them to appreciate that theories are tentative best explanations that may later be replaced by better explanations. The method thus encourages them to see knowledge as mutable, rather than authoritative and definitive. In knowledge building, the principle of improvable ideas holds that knowledge is created by knowledge workers (e.g., scientists and engineers) who treat ideas as conceptual artifacts (Popper 1972) that can be continually improved (Bereiter 2005). This principle encourages students to treat ideas as conceptual objects that can be replaced with better ones. Through a sustained process of idea improvement, students gain deeper understanding of the specific topics into which they inquire.

In terms of the amount of guidance and scaffolds provided during the inquiry, there are highly and less-structured inquiries. Highly structured inquiry provides students with a clear procedure to follow. Students are less likely to make mistakes when conducting experiments. They should know what to do because highly structured inquiry methods provide strong scaffolds and guidance. The limitation of structured inquiry is that the inquiry problem is predetermined rather than formulated by the students themselves (Collins 1996; Martin-Hansen 2002). Clear guidelines mean that students have less opportunity to try other ways of approaching a problem. In contrast, in less-structured inquiry, students are not given clear guidance on how to proceed. It is more student-driven as students identify the problem to be addressed and make and revise their inquiry plans accordingly (Bell et al. 2005; Riga et al. 2017). This kind of inquiry is more aligned to real-world scientific inquiry and thus more authentic. Although students will spend more time working out how to proceed, less-structured inquiry gives them more scope to test their ideas. Knowledge building is a pedagogy that is minimally structured at the epistemic level. It only specifies generic principles for creating an environment that is psychologically safe for students to engage in more open-ended, inquiry-based learning. Students are empowered to identify problems of interest based on their real-life experience and subsequently to address their inquiry and to work creatively and scientifically with ideas. Through such a less-structured inquiry process, students' epistemic agency could be enhanced to the level of knowledge workers such as scientists or inventors whose main cognitive focus is on the ideas.

Collaborative, student-driven inquiry emulates the practices of the scientific community (Bell et al. 2010). It has also been suggested that teachers should create learning environments that mimic the environments in which real-world scientific inquiry takes place (O'Neill and Polman 2004), as such environments would make it easier for students to exchange and challenge each other's ideas and come up with better theories of natural phenomena. More student-centered and open-ended approaches have been widely adopted in recent decades, such as problem-based learning or project-based learning. Knowledge building has also been applied to helping students learn in the science domain. Most previous studies of knowledge building in science learning focused on the relationships between knowledge-building activities and understanding of the nature of science (Goh et al. 2013), the measurement of community knowledge and collaboration (Hong 2011; Hong and Scardamalia 2014; Oshima et al. 2012) and students' collaborative learning outcomes (Hong et al. 2015a). Most of these studies have adopted Knowledge Forum as the main online platform. Knowledge Forum was developed according to knowledge-building principles to support sustained community idea development (for details, see Scardamalia 2004; Scardamalia and Bereiter 2006, 2010); nevertheless, fewer studies have carried out in-depth investigations into how specific mechanisms in Knowledge Forum help to facilitate students' inquiry and concept advancement.

Furthermore, although knowledge building along with Knowledge Forum has been applied successfully in many subjects, from languages and the fine arts to STEM, school levels from preschool to postgraduate, and cultural contexts in both western and eastern countries (Chen and Hong 2016; Yee 2017), in Taiwan, science curricula have still been strongly influenced by traditional Chinese test-driven approaches. It was not until the 1990s that the Ministry of Education started to promote a series of education reforms, emphasizing the importance of scientific literacy and the practice of inquiry in science education. Nevertheless, the inquiry models presented in the current secondary school textbooks still hold a more structured experimental view (see a special section particularly talking about Taiwan in Abd-El-Khalick et al. 2004). In addition, studies also indicate that Taiwanese junior high school teachers still hold a more empiricist view of the nature of science and laboratory activities (Lee et al. 2008), which may lead them to teach using a more content-based approach.

Hence, this study aimed to create a less-structured, collaborative, and web-based inquiry applying the principles of knowledge building. How do specific Knowledge Forum activities influence students' less-structured inquiry, and how do students actually conduct online inquiries? To address these issues, our study poses the following specific research questions:

Is there any positive change regarding the level of scientific concepts students have worked with online in Knowledge Forum from the early to later knowledge-building stages?

Are students' online Knowledge Forum activities related to the development of more sophisticated scientific concepts?

What types of online activities do most to enhance the quality of students' scientific inquiries?

How do students conduct scientific inquiries and discussion in Knowledge Forum?

Method

Participants and Pedagogical Design

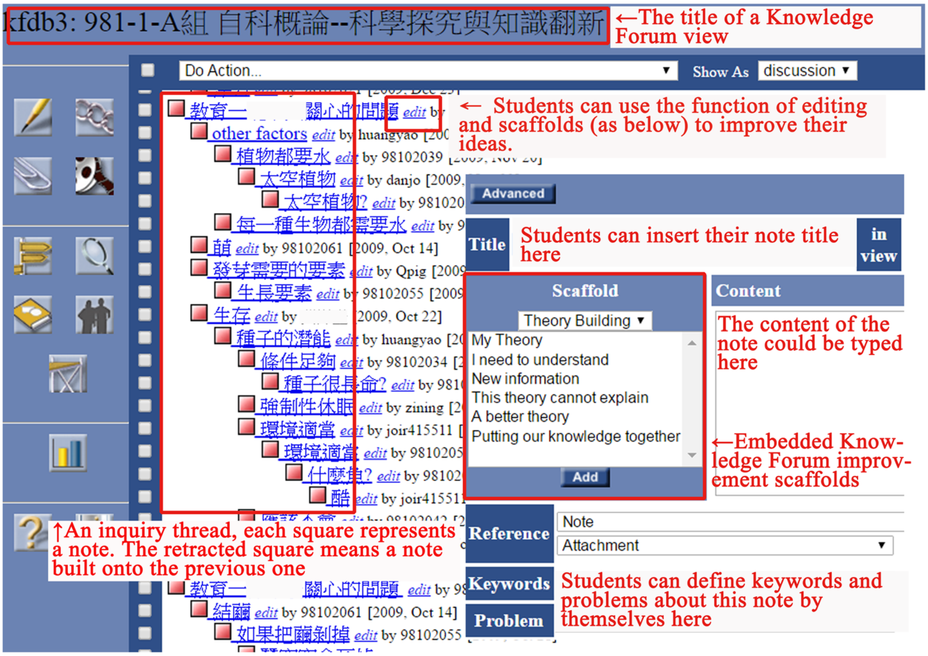
The participants were 52 undergraduate students in a degree program of general education (39 freshmen, 13 sophomores) who took an 18-week course entitled "Introduction to Natural

Sciences.” The course was designed (1) to prepare these prospective teachers to teach natural sciences and (2) to help them develop more sophisticated approaches to scientific inquiry so that when they become teachers, they will be equipped to engage students in constructivist science inquiry. Depending on the nature of the questions, different experiments that students learned from their middle and high schools were referred to in addressing their inquiry questions. As this is an introduction course to natural science for non-science major students and there is no lab provided for this course; no real-world experiments were performed in this class.

Knowledge-building pedagogy was used to design a collaborative environment in which students could work on ideas and co-construct scientific knowledge as a community. Knowledge Forum was used in this course to facilitate students’ inquiries. Specifically, the following activities were conducted on Knowledge Forum:

1. Identification of problems and definition of activities: At the beginning of the course students were invited to identify as many real-life science problems as possible (e.g., “Why don’t plastic bags decompose?”). This way of identifying problems is based on the knowledge-building principle authentic problems, real ideas which highlight that knowledge problems should arise from learners’ efforts to understand the world around them, as this will motivate them to improve their understanding. This approach is very different from the typical method of teaching science, which involves all students working on the same problems that are assigned by the teacher or taken from a textbook.
2. Idea diversification and exchange activities: In line with the knowledge-building principle of idea diversity, students were encouraged to generate as many ideas as possible. A diversity of ideas is as essential to sustaining knowledge creation as biodiversity is to the success of an ecosystem. This is also very different from typical classroom practice, which prioritizes knowledge acquisition while disempowering the value of using ideas for knowledge creation.
3. Idea elaboration and reflection activities: In line with the knowledge-building principle of improvable ideas, students were encouraged to treat all the ideas they contributed to the forum as improvable; they were encouraged to work and reflect collaboratively in order to improve the quality and validity of all the ideas circulating in the community.
4. Idea integration and problem resolution activities: In line with the knowledge-building principle of rise above, students were encouraged to work towards a more comprehensive, higher level conceptualization of problems to advance their conceptual understanding. At the same time, they were also encouraged to identify further problems emerging from their knowledge-building activities and to address them in subsequent inquiry activities.

As a computer-supported collaborative knowledge-building environment, Knowledge Forum represents a communal knowledge space to which students can contribute ideas, in the form of notes, to virtual “spaces” or “views” for collaborative discussion and inquiry among a community (e.g., a class). Knowledge Forum offers several ways to engage in collaborative idea improvement. Participants can build on or annotate others’ notes, co-author notes, add keywords, and create “rise-above” or “summarizing” notes that integrate related ideas to address problems which the community is inquiring into. Knowledge Forum also has a set of six knowledge-building scaffolds that can be used to help users improve their ideas: (1) My theory; (2) I need to understand; (3) New information; (4) This theory cannot explain; (5) A better theory; and (6) Putting our knowledge together. These Knowledge Forum activities (see Fig. 1)—contributing, reading, interacting/collaborating/linking, and revising/scaffolding/



←The title of a Knowledge Forum view

← Students can use the function of editing and scaffolds (as below) to improve their ideas.

Students can insert their note title here

The content of the note could be typed here

←Embedded Knowledge Forum improvement scaffolds

↑An inquiry thread, each square represents a note. The retracted square means a note built onto the previous one

Students can define keywords and problems about this note by themselves here

Fig. 1 Knowledge Forum and examples of views and notes

editing—are automatically recorded in a database and summarized statistically using a built-in tool called the Analytic Toolkit.

There were two phases of the knowledge-building activities in this course, with the ninth week (midterm exam) as the separation point. In the first knowledge-building (KB) stage (weeks 1 to 9), the instructional design emphasis was on problem generalization and idea diversification. For example, during the first 2 weeks, students were encouraged to post all the questions in which they were interested. These questions should be generated from their daily lives, which reflect the KB principle of authentic problems. Questions are posted using the KF scaffold: “I need to understand…” Students then responded to each other, posting their ideas and related information using KF scaffolds such as “new information…” or “my theory….” The ideas could come from either students’ own hypotheses or the resources from any media, as long as they supported the students’ own claims. The discussion threads would be shown as in Fig. 1, each square behind the previous one representing a student response to the other. In the latter half of the course (weeks 10 to 18), the students started to clarify issues and elaborate more sophisticated explanations of scientific concepts, using KF scaffolds such as “this theory cannot explain…” to identify gaps in the ideas, or “a better theory…” to propose better explanations. Students were also encouraged to use the “putting our knowledge together” scaffold to summarize all the information raised during the whole discussion thread, and to formulate a convincing explanation or theory. Although the students were encouraged to generalize, diversify, elaborate, then converge their ideas during the first and last phases, there were no strict rules that they had to follow this process. Hence, it was possible for them to try to elaborate their ideas during the first stage, while they still tried to raise questions that interested them during the second. The activities are student-centered and learner-driven. The teacher provided minimum interventions to students’ KF discussion during the whole learning process.

Data Source and Analysis

Data were mainly drawn from the records of the students' online inquiries, discussion, and interactions, and were analyzed as described below:

Level of Students' Online Inquiry To understand the first research question regarding whether students' scientific concepts became more sophisticated, we adapted the coding scheme originally developed by Zhang et al. (2007) to analyze the data derived from the students' Knowledge Forum discussions. The scheme consists of six levels of science-related conceptual development: (1) non-scientific concept; (2) pre-scientific concept; (3) hybrid concept; (4) basically scientific concept; (5) scientific concept; and (6) scientific concept-based theory building. Following a similar procedure to that outlined above for inter-rater agreement, the same two researchers independently rated a randomly selected 30% sample of the students' online discussion. The reliability coefficient computed using the Spearman correlation (γ) was .76 ($p < .001$). Table 1 shows the coding scheme employed in this study. For the purpose of analysis, we divided the whole semester into two KB stages (early and late KB) using the midterm examination as the boundary. We also classified the science-related concepts as less sophisticated concepts (levels 1–3) or more sophisticated concepts (levels 4–6). Before the analysis was made, the distribution of the data was examined. This scientific inquiry data set distribution showed a Kolmogorov-Smirnov (K-S) statistic of 0.19 ($\mathrm{df} = 52$, $p < 0.001$). As it did not represent a normal distribution, a non-parametric statistical method was used to determine whether there was a difference between students' scientific concepts in the early versus the late KB stages. Table 1 shows the coding scheme and descriptions of the six science-related concepts.

Scoring of Student's Scientific Inquiry Activities To answer the second and third research questions, which are to understand how students' scientific concepts are related to the online activities, all the notes posted in Knowledge Forum were given a score ranging from one to six, based on the coding scheme shown in Table 1. Thus notes predominantly discussing non-scientific concepts scored one, while the rare notes that provided evidence of scientific concept-based theory building scored six.

Online Activities Online activities were recorded automatically in the Knowledge Forum database, extracted by the Analytic Toolkit for Knowledge Forum (ATK). There are four types of online activities that support sustained improvement in ideas: contributing activity, indexed as the average number of notes contributed per student; reading activity, indexed by the average number of notes read; collaborative activity, indexed as the average number of built-on notes; and improvement activity, indexed as the average number of notes revised and the average number of scaffolds used to facilitate scientific inquiry. To engage students in working innovatively with ideas for advancing knowledge, members in the knowledge-building community not only need to generate ideas (contribute) and learn about one another's ideas (read) but also need to broaden their thinking and exchange ideas (collaborate) and to elaborate, connect, and reflect on the pool of ideas (improve) (Hong and Sullivan 2009). We hypothesized that students' online inquiries would be more productive and effective if they used all these ways of working with ideas. If this were the case, students' online activities would be highly correlated with their online inquiry activity. In other words, the greater the students' involvement in contributing, reading, collaborating, and improving ideas to advance the community's knowledge, the higher the quality of their scientific inquiries would be. To

Table 1 The coding scheme used to classify scientific concepts in students' essays

Category	Description	Examples
Non-scientific concept	Student does not address the question, instead expressing emotion or chatting to other students.	Well, I do not remember it. But this is a good way. I will hang on and dry my jeans from inside out. The plastic bag is not delicious~ That is what bacteria think? Though I think this thought is kind of cute.
Pre-scientific concept	Student responds to the question naively or based on personal experience.	So this means that we study so hard that we grow white hair. If the iceberg is high enough, there is not just a little bit floating above the sea! Icebergs are just like houses, buildings under the sea.
Hybrid concept	Student responds to the question based on personal experience and understanding of the scientific knowledge.	I think it is because of the relationship between volume and distance. Or maybe the planets attract each other. I think the salmon trout remember the location and direction by nature. Just like they were born with GPS inside their body.
Basically scientific concept	Student responds to the questions using scientific knowledge but without examples or explanation.	Maybe a proper environment helps provide needed stimulation. It makes the chemical reaction take place within seeds, making the cells divide rapidly. The basketball can bounce, which may be to do with action and reaction.
Scientific concept	Student responds to the question with concrete and clear scientific knowledge.	It seems feathers cover all of a bird's body. Actually, birds which can fly have a naked place around the neck, backside, abdomen and side of the body. This helps the contraction of the muscles. The flying fish is shorter and flatter in the body. The reason for their name is that they have a pectoral fin that is more than half their body length.
Scientific concept based theory building	The student draws on previous discussion and scientific concepts to suggest an explanation or hypothesis that may help resolve the question or problem under consideration. In other words, this category denotes participants' efforts to connect scientific concepts to formulate hypotheses or emerging theories.	I myself am also not sure about whether static electricity could be collected and used as a main source of power [for home and factory]. My theory is that as a type of energy, static electricity is not being collected because of its lack of practical value on an economic scale… and because human beings have not developed the necessary machine for such collecting purposes.

Adapted from: Zhang et al. (2007)

$r = .76$, $p < .001$

determine whether this was the case for our participants, as the second research question, we calculated the Spearman correlations between the six levels of science-related concepts described above and participation in the four types of online activity. In addition, stepwise regression was performed to examine the relationship between students' online activities and their scientific concept scores.

Results

Analysis of Students' Scientific Concepts

To answer the first research question, whether there is any overall change in terms of the level of scientific concepts that students worked with online in Knowledge Forum from the early to the later knowledge-building stages, students' online discussion was parsed and analyzed using a non-parametric statistic and the coding scheme described in the previous session (see Table 1). Table 2 shows the changes in overall numbers of students' inquiry notes posted on Knowledge Forum from the early to the latter stage. The results based on a non-parametric statistic showed a significant decline in the students' notes from the early to the latter stage ($z = -2.44$, $p < 0.05$). However, to know whether the quality of scientific inquiry was enhanced while the number of their notes declined in the latter stage, further analyses examined the relationship between their inquiry activities. As shown in Table 2, there was a significant difference in students' numbers of low-level inquiry activities (including "non-scientific concept," "pre-scientific concept," and "hybrid concept") ($z = -2.87$, $p < 0.01$), and numbers of high-level inquiry activities (including "basic-scientific concept," "scientific concept," and "scientific concept-based theory building") were not significant ($z = -1.03$, $p = 0.31$).

The instruction design in this course encourages students to produce ideas freely about the problems concerned. Therefore, during the early stage, which focuses on idea generation, more diverse ideas including both less and more sophisticated concepts would be raised. After the midterm examination, the students started to focus more on idea elaboration and integration. Thus, the findings show a greater quantity of both kinds of concepts during the early stage while, in the later stage, they raised significantly fewer naïve concepts, representing that they might potentially pay more attention to elaborating their ideas to ensure better quality ideas in the later KB stage.

Relationships Between Online Activity and Inquiry Processes

To answer the second research question about whether students' online activities relate to their inquiry levels, we began by examining the overall status of the online activities. Firstly, the

Table 2 *t* test of students' number of inquiry notes and change in level of scientific concepts in the early and latter stages

	Number of notes				*z*
	Early KB		Late KB		
	M (%)	*SD*	*M (%)*	*SD*	
Overall notes posted	4.38 (100%)	4.47	3.18 (100%)	2.96	-2.44^{*}
Less sophisticated concepts	2.18 (49.8%)	3.06	1.31 (41.2%)	1.87	-2.87^{**}
More sophisticated concepts	2.20 (50.2%)	2.37	1.87 (58.8%)	1.70	-1.03

$^{**}p < .01$ $^{*}p < .05$

distribution of the dataset based on all the online activities was examined using K-S statistics, showing a result of 0.167 (df = 52, $p < 0.01$). As a reference, this data set did not represent a normal distribution. Overall, 1094 notes were posted. As mentioned above in the literature review, knowledge building goes beyond group-based learning, with all participants working as a community and the whole community space being used for collaboration and joint work on ideas. All participants can work together in groups on one idea of their interest and then regroup to work on another idea. As a result, there was a total of 111 questions raised within all 1094 notes. Among all questions, 17 were identified as long-lasting driving questions and the rest were questions that were only briefly touched upon and then ignored due to irrelevance or disinterest, or related but trivial questions that were derived from the main driving questions, or subordinate questions that could help further clarify or explain the driving questions. As all students in the community are treated as legitimate knowledge contributors based on knowledge-building principles, they are allowed to contribute ideas in any discussions if they are interested in certain ideas. Basically, each of the 17 driving questions represented a discussion thread. Most of these 17 threads lasted for the whole semester, though not every question was discussed every week. Given the spirit of open-ended inquiry and the nature of an idea-centered discussion (meaning that students can join any discussion thread based on their interest in certain ideas), students might discuss plastic bags 1 week, the properties of human hair the next. The week after, they might go back to discuss the plastic bag question further, while engaging in human hair discussion as well. Nevertheless, the Knowledge Forum log showed that students consistently engaged in open-ended knowledge-building inquiry activities for the whole semester. To sum up, reading activity was indexed as the percentage of notes being read ($M = 22\%$, $SD = 14.2\%$) and the percentage of reads (i.e., a note could be read more than once) ($M = 53.6\%$, $SD = 32.4\%$) by the students, contributing activity was the number of notes each student created without building on to others' ($M = 3.5$, $SD = 2.6$), collaboration activity was the number of building-on notes (($M = 18.5$, $SD = 14.7$), and the percentage their notes linked with each other's ($M = 78.5\%$, $SD = 25.4\%$), and improvement activity was the number of notes revised ($M = 4.6$; $SD = 8.8$) and the average number of scaffolds used to facilitate scientific inquiry ($M = 16.5$, $SD = 17.3$). The next step was to determine whether the quality of students' inquiries (in terms of the six levels of science-related concepts) was related to their online activities. As shown in Table 3, we found that quality of inquiry was correlated with the overall volume of online activity ($\rho = .79$, $p < .001$). Further analysis showed that quality of inquiry was correlated with all four specific types of online activities: reading activities ($\rho = .49$, $p < .001$), contributing activities ($\rho = .31$, $p < .05$), collaboration activities ($\rho = .64$, $p < .001$), and improvement activities ($\rho = .62$, $p < .001$). These results indicate that the more actively students were involved in online idea improvement activities, the more likely it was that they were discussing and inquiring into more sophisticated scientific concepts.

Table 3 Spearman's correlations between level of scientific inquiry and online activity

	Reading activity	Contributing activity	Collaboration activity	Improvement activity	All activities combined
Level of scientific inquiry	$.49^{***}$	$.31^{*}$	$.64^{***}$	$.62^{***}$	$.79^{***}$

$^{*}p < .05$, $^{***}p < .001$

Associations Between Students' Online Activities and Quality of Scientific Inquiry Activities

Although all four types of online activity were correlated with the level of scientific inquiry, it is possible that different types of activity may contribute differently to the quality of inquiry. To examine the relationships between type of online activity and inquiry quality in more detail, we carried out stepwise regression. Table 4 shows the results. Scores for level of scientific inquiry were predicted best by online activities according to Table 4.

According to the results shown in Table 4, improvement activity can explain 41% variance in the scientific inquiry score, collaboration activity can explain 13% variance in the scientific inquiry score, while contributing activity can only explain 6% of the scientific inquiry. This means the improvement activity in KF is the most important of the knowledge-building activities in students' scientific inquiry performance.

When conducting the online scientific inquiries, the first thing the students usually did was to read the notes written by others to familiarize themselves with the emerging issues of concern to the community. However, our analysis indicates that reading notes without also contributing, interacting, or improving was not likely to advance the inquiry or improve students' conceptual understanding of the topics discussed. Contributing ideas by posting notes was a key type of online activity, but the level of collaboration influenced whether the various ideas that were posted were appropriately linked to each other. This was why contributing activity was not the only positive predictor of the quality of students' scientific inquiry. Collaboration was another key type of online activity. Sharing and discussing their ideas and thoughts with others helped the students to improve their understanding of the concepts and issues concerned. This may be why collaboration activity emerged as a contributor to high inquiry quality. The last key type of online activity was idea improvement. This emerged as the best predictor of inquiry quality score. Involvement in improvement activity indicated that the students were able to self-monitor and revise their previous ideas. They could also contribute to communal idea improvement using the "scaffold" functions to suggest better theories based on others' ideas. Improvement activity raised the quality of the scientific concepts used by students and thus contributed more to inquiry quality than the other forms of activity.

A Case Example of the Online Inquiry Process—How Students Revised their Ideas

To further understand how the students conducted their inquiry using KF as a tool, Fig. 2 shows an example of how they inquired into the Coriolis effect. Overall, this discussion thread

Table 4 Stepwise regression of four kinds of online activity—scores of scientific inquiry

	Predictor	β	Adjusted R^2	ΔR^2	F
Model 1	Improvement activity	0.65^{***}	0.41		36.39^{***}
Model 2	Improvement activity	0.52^{***}	0.54	0.13	30.65^{***}
	Collaboration activity	0.39^{***}			
Model 3	Improvement activity	0.45^{***}	0.60	0.06	26.19^{***}
	Collaboration activity	0.40^{***}			
	Contributing activity	0.27^{**}			

Table excludes reading activity, model 3, df regression = 3, df error = 48

$^{**}p < .01$, $^{***}p < .001$

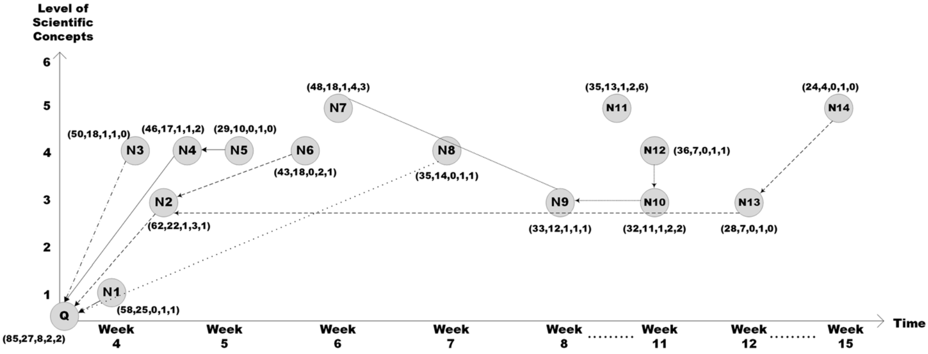


Fig. 2 The inquiry trajectory of the Coriolis effect thread. Note: The number (No.) shown below each note represents the number of times the note was read, the number of people who read this note, the number of notes built on to this note, and the number of times this note was revised. Arrowed lines between notes represent built-on connections from a note to another note

has 15 key notes in total, and it lasted from week 4 to week 15. Figure 2 presents the inquiry trajectory along with a timeline showing when each note was posted. The *y*-axis represents the difficulty level of the scientific concept each note is dealing with. The number below each note represents the total number of times a note was read, the number of people who read this note, the number of additional notes being built on to this note, and the number of times that this note was revised. This inquiry thread began with a note titled "whirlpool in the washbasin," in which a student asked: "I'd like to know why water in the wash basin swirls into a pipe? (Q) (Oct. 9; by B. Ju)."

The first response to this question started from student Y. Wu's intuition, following a rather naïve hypothesis: "[My idea/theory is:] because you push water when you wash your hands (N1) (Oct. 9; by Y. Wu)." Later, another student responded: "[My idea/theory is:] I think it is because of the magnetic field, and the swirling direction will be different depending on whether you're in the Southern or Northern hemisphere (N2) (Oct. 10, by J. Wu)." This student brought the concept of magnetic fields into her explanation; nevertheless, through her note writing, she did not explain how magnetic fields work or how they might influence the direction of water flow.

Later, another student proposed an alternative explanation, based on the shape of the washbasin, the Coriolis effect: "I had this question when I was in kindergarten…I think it is also because of the round shape of the basin. When water flows down into the center, water molecules will squeeze each other, hence forming a whirlpool for water to enter the draining pipe. Another idea is the Coriolis effect. It causes water to flow into the pipe in a slightly curved way (N3) (Oct. 14; by Y. Lin)." This new information prompted the student who had introduced magnetic fields into the discussion to revise his idea, adding in further explanations: "[My idea/theory is]: Since the direction of water flow is different in the northern and southern hemisphere, I agree that the idea of the Coriolis effect seems more possible as the cause. This is because the Earth is rotating…and the Earth's rotation produces a Coriolis effect, which contributes to the phenomenon you [the original questioner] described [i.e., how water flows in a washbasin]. I think this makes better sense. So the initial idea about magnetic fields that I intuitively suggested in the first place seems to have little to do with the phenomenon, and I now think the Coriolis effect is a better explanation for the question (N6) (Oct. 18; by J. Wu)." The student Y. Wu later revised his potential idea that the Coriolis effect is a better explanation (N6) as compared with the magnetic (N2) idea for this phenomenon. Nevertheless, though the

Coriolis effect had been introduced by Y. Lin (N3), it had not yet been clearly defined and examples were lacking. A later note by the instructor was posted to help the students clarify the concept: "What is the Coriolis effect?" (This note was not counted in the thread in Fig. 2). The next post/note then further responded to this question by providing a more concrete definition with an example to explain the Coriolis effect: "We have learned about the Coriolis effect in our senior high school. It is caused by the earth's rotation bias…...." (this student's note further explains its influence and examples) (N7) (Oct. 15; by R. Xu).

In the meantime, other students thought that, in addition to the Coriolis effect, there might be alternative explanations for the swirling of water down a sink: [My idea/theory is] the Coriolis effect has a relationship with the earth's rotation. In terms of only a small object like a sink, do we really need to adopt a formal theory to answer this question; couldn't we just try to address this problem based on our daily life experience and observation? (N9) (Nov.2; by Y. Wu). This student doubted that there could be alternative explanations or additional evidence that could be gathered from micro-level observations, in addition to just trying to adopt a macrolevel theory such as the Coriolis effect to address this inquiry question fully. Another student replied to this note by raising another issue: "[I need to understand] if we were not to adopt the Coriolis effect to explain this, how about trying to find explanations based on 'daily life' experience or observation? Don't things affect each other from macro to micro level? (N10) (Nov. 20, by C. Lai)." Some also brought up more related questions such as why water always flows into a pipe (N5), while others mentioned additional factors such as gravitational and frictional force (N6, N12). After continual discussion, exchange of arguments, and sharing of more factual information, with all ideas contributed in the form of notes to Knowledge Forum (KF), the students began to try to systematically and integrally summarize all contributed ideas, using the rise-above function in KF, by considering the main debate between those who favored the Coriolis effect as the key factor and those who preferred to additionally consider other factors based on daily life observation, such as the friction caused by the sink materials and the shape of the sink, as well as the place where the pipe is installed. They reached a temporary conclusion that: "[Putting all ideas/theories together]: we think it's perhaps not just because of the Coriolis effect. The Coriolis effect mainly affects water flow on a bigger scale. But within a limited area as small as a washbasin, other factors such as surface friction, viscosity, the location of the draining [in the middle or not], the shape of the container, etc., to a certain extent may also have more influence on how water flows than the pure influence caused by the Coriolis effect (N11) (Nov. 23, by J. Sun)." The students therefore reached a temporary interrelated conclusion that, although the Coriolis effect may be one of the key factors influencing the flow of water, the shape of the washbasin, its material quality, and the placement of the drainage point are also important factors that need to be taken into overall consideration when considering how water flows. After that, there was still some more discussion with related questions about the direction of the swirl, but no further conclusion was made by the end of this inquiry thread besides N11.

Discussion and Conclusion

The aim of this study was to investigate (1) whether engaging students in knowledge-building activities would help them develop more sophisticated scientific concepts, (2) how specific activities influenced the quality of students' scientific inquiries, and (3) how students actually conducted their online scientific inquiries via Knowledge Forum. The results indicated that the students progressed towards more sophisticated scientific concepts in the later stage of knowledge building. We also found that their scientific conceptual understanding was correlated with the volume of their online Knowledge Forum activities. Furthermore, different types of online inquiry activity contributed differently to the quality of their scientific inquiries. Overall, online *improvement* activity was the most important positive influence on inquiry quality scores, with online *collaboration* activity the second most important factor; online idea *contributing* activity had less influence on inquiry quality scores. Merely reading each other's notes (i.e., idea awareness) without contributing, collaboration, or improvement had no effect on inquiry quality.

The results from our study basically support our claim that with the use of an online environment designed to have the requisite pedagogical features (e.g., Knowledge Forum), it is possible for students to conduct open-ended inquiries like those of the scientific community, in the science classroom. Eminent psychologists such as Dewey (1910), Piaget (1976), and Vygotsky (1978) recognized that acting as scientists is crucial to children's development, and considered open-ended inquiries an important form of such activity (White et al. 1999). Although scientific inquiry is highly valued in science education, teachers may have difficulty implementing inquiry-based curricula due to constraints on time, the course structure, or because, in practice, it is hard to implement inquiry learning in science (Banerjee 2010; Bartos and Lederman 2014). Some teachers may rely on highly structured, teacher-oriented pedagogical methods (e.g., lectures) that have the benefit of enabling students to acquire a great deal of knowledge and a great breadth of knowledge (Kang and Keinonen 2017). Highly scripted, structured inquiry-based teaching is also easier for novice teachers than open-ended inquiry-based teaching. Nevertheless, it has been suggested that learning should move from lower-level (structured inquiry) to higher-level (open inquiry) forms of inquiry. But it is clearly not easy for new teachers to handle open-ended inquiry and help students advance their inquiry to a more complex level (Bell et al. 2005). The limited time in which to cover a great deal of science material content and lack of ability to guide students' inquiries may mean that novice teachers are not willing to conduct open inquiries in the classroom. Our study has shown that providing a principle-based knowledge-building environment that permits reading, building on, and consolidating online co-construction of scientific concepts and theories supports open inquiries. Our results indicate that open inquiry-based learning has a positive impact on students' conceptual understanding.

Furthermore, the quality of students' scientific concepts was correlated with their engagement in their inquiry community. This study extended previous research by examining how the different types of online activity influenced students' level of scientific conceptual understanding. The regression results indicate that merely reading others' notes to be aware of their ideas did not improve the quality of students' ideas. Only when students contributed their ideas to the community, connected their ideas to those of others, and continually revised and improved their ideas did their online activities contribute to better understanding of scientific concepts and a better quality of scientific inquiry among students. Qualitative analysis also showed that students did consciously revise their previous ideas as a result of reading and interacting with other theories. We therefore suggest that in future inquiry-based learning, teachers should put more emphasis on reflection on ideas, be they one's own or those of one's peers.

Another suggestion derived from this study concerns technology. In general, leveraging the ever increasing power of learning analytics to help shape and promote desirable learning performance has been a key thrust of continuous research among researchers associated with the knowledge-building pedagogy (Chen et al. 2017). For this study, given the importance of improvement activities, science educators may need to consider how to promote such activities together with education technologists. This is likely to require closer examination of how improvement activities are constituted in the semantic structure during dialogical theory building processes. At a very broad level, a revised note is likely to consist of more statements and scientific concepts. It is not difficult for computers to track how many statements are made in a note and how many more are made in subsequent revised notes. At the semantic level, science educators who specialize in scientific language structure need to unpack how scientific statements are formulated and use analytic tools to track if there are more such statements. As for the content aspect, there is a need to track the scientific concepts for the phenomenon under investigation, which implies that the community-based database needs to be linked to scientific corpus databases. This would also broaden the perspective of the local communities and connect them to higher level authentic scientific works. Coordinating these aspects of work to generate indicators for improvement activities and to prompt students to consider associated science concepts leverages the power of pedagogical gamification and the power of semantic networks. However, while we could imagine how to promote the improvement activities, to gauge the work needed for such technological intervention is beyond the expertise of the authors.

Admittedly, this study has some other limitations. Firstly, since there was no comparison group, we could not determine whether there was a causal relationship between the Knowledge Forum activities and the quality of the students' scientific inquiries. Our results do, however, indicate that these variables were correlated, and the results based on regression analysis showed a possible prediction of the relationships. We suggest, therefore, that in future research using similar instructional designs, a control group should be included to compare the effects of structured and open-ended online inquiry. As most science education still takes place face-to-face, we also suggest that there should be research comparing online, face-to-face, and blended learning interventions to explore potential differences between learning environments. Secondly, this study was conducted in Taiwan, and although we found that open-ended inquiry-based learning had positive effects, caution should be exercised in generalizing the findings to other cultural contexts.

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