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Fostering sustained idea improvement with principle-based knowledge building analytic tools

Huang-Yao Hong [a,*], Marlene Scardamalia [b], Richard Messina [c], Chew Lee Teo [d]

[a] Department of Education, National Chengchi University, Taiwan
[b] Institute for Knowledge Innovation and Technology, University of Toronto, Canada
[c] Dr. Eric Jackman Institute of Child Study (OISE), University of Toronto, Canada
[d] Ministry of Education, Singapore

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ABSTRACT

The purpose of this study is to explore the use of principle-based analytic tools to improve community knowledge building in a class of Grade 5/6 students. A flexible design framework was used to engage students in use of three analytic tools—a Vocabulary Analyzer, a Social Network Tool, and a Semantic Overlap Tool. These tools are built into Knowledge Forum technology so principle-based assessment is integral to knowledge work. The primary source of data was discourse generated by students in Knowledge Forum over a school semester (approximately four months). Findings based on a mixed-methods analysis reveal principle-based knowledge building analytic tools to be effective in increasing the frequency with which key terms are used by individuals, in their own productive vocabulary as well as in the shared community space, thus creating a more discursively connected community. Results additionally show a shift from problem generation and breadth of inquiry to increased self-assessment, reflection, and depth of inquiry; also, students report significant ways in which knowledge building analytic tools can increase knowledge building capacity.

1. Introduction

Knowledge Building[1] is a social process focused on production and sustained improvement of ideas valuable to a community (Scardamalia & Bereiter, 2003, 2006). Knowledge building principles represent design ideals, challenges, and improvable objects in their own right (Scardamalia, 2002; Scardamalia & Bereiter, 2006). The Knowledge Building conceptual framework underlies Knowledge Forum technology and its analytical tools (cf. Ali, Asadi, Gašević, Jovanović, & Hatala, 2013) that are designed to extend both individual and community capacity for engaging in challenging knowledge work (Scardamalia, 2003, 2004).

Knowledge Forum provides a community knowledge space for community members to work with ideas (Hong, Chang, & Chai, 2014; Hong & Chiu, in press). Students enter notes into a virtual problem-solving space (a "view" in Knowledge Forum),

* Corresponding author. National Chengchi University, No. 64, Sec. 2, Zhinan Rd., Wenshan District, Taipei 11605, Taiwan.
E-mail address: hyhong@nccu.edu.tw (H.-Y. Hong).

[1] Because the term "knowledge building" now appears in many documents, often without definition, we use lower case with the generic term and capitalize Knowledge Building when referring to the approach originating in the University of Toronto Knowledge Building laboratory and promoted by organizations such as Knowledge Building International.

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thus externalizing their ideas so that community members can engage in collaborative discourse. Participants contribute individual and co-authored notes, build on and annotate the notes of others, add keywords, and create rise-above notes to synthesize different notes with related ideas. Knowledge-building activities (e.g., generating and revising ideas, reading and building on ideas of others, linking ideas, and so forth) are recorded in the Knowledge Forum database. An analytic toolkit underlying Knowledge Forum captures data for automated analysis, enabling visualizations that provide feedback to users.

In this particular study, we tested three new tools including a Vocabulary Analyzer, a Social Network Tool, and a Semantic Overlap Tool. The Vocabulary Analyzer has been developed to trace the growth of a user's vocabulary over time and to assess a user's vocabulary level against words entered into a pre-defined dictionary (for example, words considered important for use when working in a specific domain or concepts identified as important in curriculum guidelines). The Social Network tool can be used to assess group dynamics or community members' interactivity; for instance, which community members are collaborating with each other, as indicated by response to their work. Those working in isolation are evident because of the lack of interaction. The Social Network tool also shows the number of notes a community member builds on, links to, references, annotates, or in other ways interacts with. The Semantic Overlap tool is used to compare key terms or keywords extracted from different notes (or sets of notes) and to indicate the overlapping words or phrases. The overlap tool can work with any evaluative criteria that community members select, such as curriculum guidelines or readings for a unit. Thus for example, the overlap between terms in the student discourse and concepts identified in curriculum guidelines can be assessed. The Semantic Overlap tool can also be used to identify idea similarity, as indicated by the key terms shared between members. Fig. 1 illustrates how the three tools are integrated into Knowledge Forum and provides an example of a view and a note. Figs. 2–4 further show the interface of each of the three tools and important tool features.

1.1. Principle-based design

An important goal of the development of new tools is to continually improve the capacity of Knowledge Forum as a knowledge-building environment. Even more challenging is establishing effective and productive knowledge practices surrounding the use of analytic tools. Issues abound; for example, under what conditions should the tools be used, and by whom—teachers, researchers, students, administrators? Can they be used for individual and group assessment, for routine evaluation and higher-level goals of knowledge advancement, and so forth? Recent work demonstrates that with carefully constructed pedagogical design, these tools can serve as powerful knowledge building tools used by even very young children (Ma, Matsuzawa, Kici, & Scardamalia, 2015; Resendes, Scardamalia, Bereiter, Chen, in press; Zhang, Hong, Scardamalia, Teo, & Morley, 2011). The current study aims to elaborate the concept of principle-based pedagogical design as a way to advance this work.

Principle-based design is theory-driven as elaborated by Scardamalia and Bereiter (2007, in press). Principle-based knowledge building analytic tools are very different from procedure-based designs that focus on efficient paths to pre-defined goals. Pre-specified instructional procedures are often highly-organized (Gagne, 1987; Gagne, Briggs, & Wager, 1988). The case for ritualistic learning activities was elaborated by Brown and Campione (1994); scripted learning benefits are elaborated by Najafi, Zhao, and Slotta (2011). While proceduralized and carefully guided instruction has been found to improve students' academic achievement (e.g., Kirschner, Sweller, & Clark, 2006), disadvantages include knowledge telling

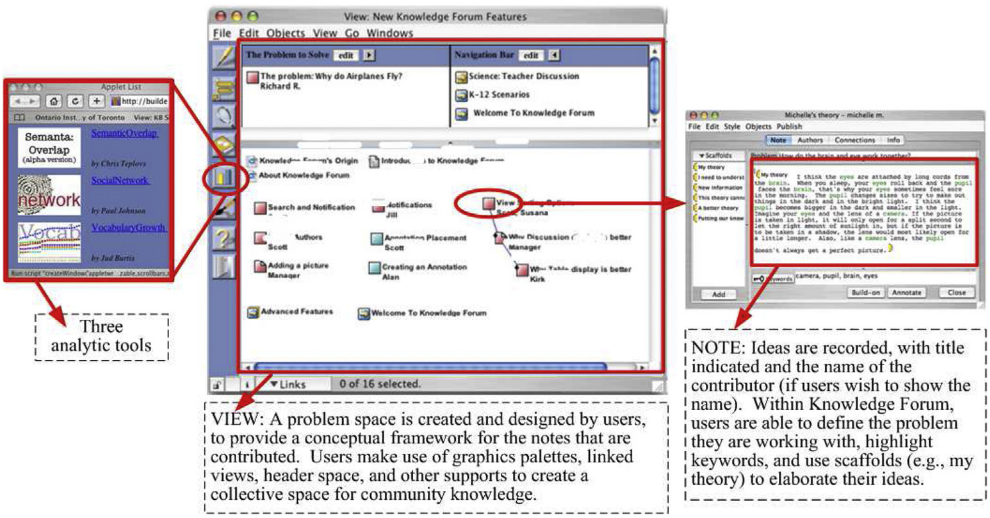

Fig. 1. Three tools and examples of a view and a note.

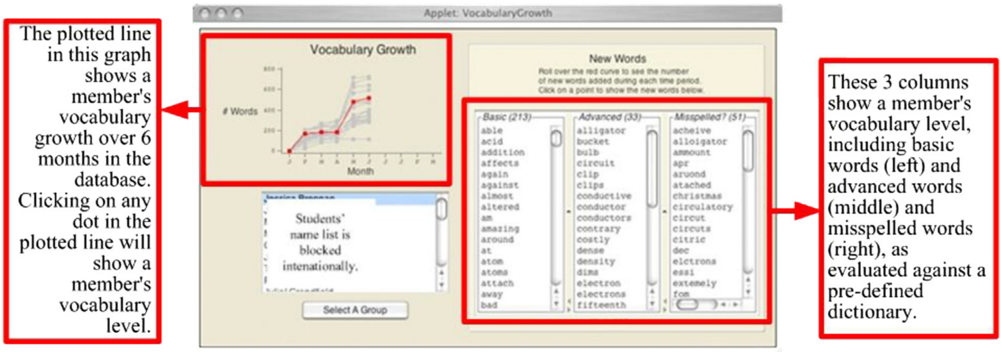

Fig. 2. Vocabulary Analyzer: Illustrating the profile of a person's vocabulary growth over time.

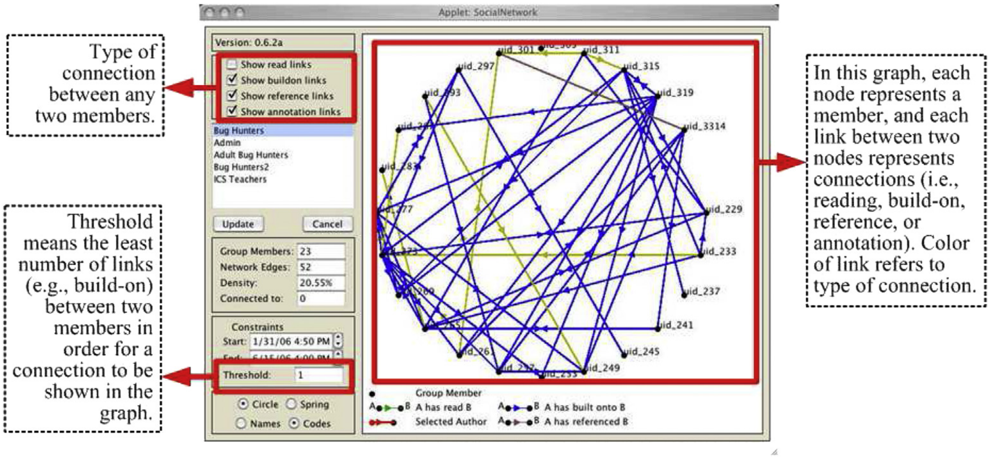

Fig. 3. Social Network Tool: Illustrating social dynamics of a community's knowledge activities.

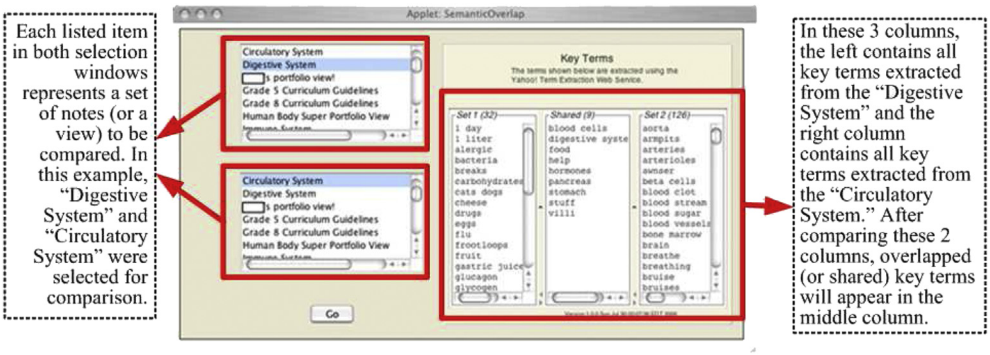

Fig. 4. Semantic Tool: Illustrating shared and non-shared key terms between two sets of notes.

rather than knowledge transforming processes and focus on well-defined rather than complex problem solving and knowledge building. The primary concern is measurable learning outcomes that often obscure creative, higher-order thinking capacity (Hong & Sullivan, 2009).

Principle-based design favors emergent goals and self-organization sustained by improvisation and adaptive procedures (Sawyer, 2011; Scardamalia & Bereiter, 2014a, 2014b, in press; Zhang et al., 2011). In the current study, a set of knowledge-building principles frame pedagogical and technological designs for advancing community knowledge (Scardamalia, 2002). The twelve knowledge-building principles that inform this work are as follows: (1) real ideas, authentic problems; (2) community knowledge, collective responsibility; (3) idea diversity; (4) improvable ideas; (5) epistemic agency; (6)

democratizing knowledge; (7) symmetric knowledge advance; (8) pervasive knowledge building; (9) constructive uses of authoritative sources; (10) knowledge-building discourse; (11) concurrent, embedded, transformative assessment; and (12) rise above. Table 1 presents a brief explanation of the principles. See Scardamalia (2002) and Zhang et al., (2011) for a more elaborate explanation of the principles and pedagogical and technological correspondences.

These principles, which underlie Knowledge Building pedagogy elaborated in this study, are indicated with italicized titles throughout the text. They represent an overall emphasis on knowledge creation—self-intentioned student and teacher efforts to move "beyond best practice" through adaptive patterns of knowledge interaction focused on knowledge advancement and increasingly more productive collaboration (Hong & Sullivan, 2009; Zhang et al., 2011).

The research issue addressed in this study is use of knowledge building analytic tools to engage learners in sustained knowledge building. We explored questions of the following sort: To what extent can tools be used to enable collaborative knowledge advancement in the community? Can the tools be used to foster both formative and summative assessment? Can principle-based tools help transform classroom practice?

2. Method

The present study was conducted in an elementary school in Toronto, Canada. The students engaged in a semester-long science class activity titled "integrated studies" and the main topic of inquiry was the "human body system"—a unit collectively identified by the class as a whole as the focus on their science work. The goal was to achieve understanding of the human body as a system composed of inter-related sub-systems. There were two major inquiry phases. In the first phase, which covered the first half of the semester, students inquired about internal body systems to gain greater understanding of how the brain, heart, blood, and cells work together. In the second phase, which covered the second half of the semester, the students inquired about the physical body as a system to gain greater understanding of how the body, hands, legs, knees, and feet work together to enable long jumps. Through these two-phases of work students explored the human body both as a biological system (first phase) and as a physical system (second phase). The participants were fifth and sixth graders ($N = 22$; 10 girls and 12 boys) from a mixed-grade class; they had been engaged in knowledge-building practices for more than five years. The teacher also had five years of experience implementing knowledge-building pedagogy and technology.

2.1. Research framework and procedures

The first inquiry phase provides baseline data, as no analytic tools were used in this phase. The three tools were introduced in, and used throughout, the second phase by means of the following processes: (1) the teacher presented the basic functions of each of the three tools to the students; (2) the teacher encouraged students to use the tools freely as their work proceeded; and (3) following a principle-based approach, students were encouraged to raise issues regarding the use and effect of the tools and the teacher supported collective discussion regarding how to use tools to advance community knowledge. For

Table 1
Brief description of the 12 knowledge building principles.

Principle	Brief description
Real ideas, authentic problems	Ideas are conceptual artifacts – real-life objects. Knowledge-related problems arise from learners' efforts to understand the world surrounding them, leading to advances of understanding that are very different from textbook problems and puzzles.
Improvable ideas	Participants regard all ideas as improvable; they work collaboratively to improve the quality and utility of ideas in the community.
Idea diversity	Diverse ideas are essential to sustained knowledge innovation, just as biodiversity is essential to the prosperity of an ecosystem.
Rise above	Community members work toward progressively more comprehensive principles and higher-level understanding of problems.
Epistemic agency	Participants deal with all aspects of knowledge problems, including knowledge goals, motivation, assessment, systematic planning–and problems normally addressed only by teachers.
Pervasive knowledge building	Knowledge innovation is not limited to particular subjects or occasions but pervades mental life—both in and out of school.
Constructive uses of authoritative sources	To understand a discipline is to be aware of its current state; this requires understanding authoritative sources as well as a critical stance toward them.
Concurrent, embedded, transformative assessment	Assessment is used to identify knowledge problems as work proceeds, to engage in self-initiated and self-directed reflection that is more rigorous than external assessment.
Community knowledge, collective responsibility	Contributions to collectively shared, top-level goals of the community are rewarded and honored as much as individual knowledge growth. Community members contribute ideas valuable to other members and share collective responsibility for achieving the overall knowledge goals of the community.
Democratizing knowledge	All participants are legitimate contributors to the shared, top-level goals of the organization and advance knowledge in the community.
Symmetric knowledge advance	Distributed expertise is highly valued among community members, who collaborate and exchange knowledge, adopting a to-give-knowledge-is-to-get-knowledge framework.
Knowledge-building discourse	Collective knowledge advances are transformed and further refined through intellectual discourse that regards community knowledge advancement as the primary goal.

example, the teacher prompted students to consider how to deepen their inquiry by identifying key ideas/concepts entered by different community members by using the semantic overlap tool to explore shared concepts. In line with knowledge building pedagogy no pre-defined step-by-step procedures were specified; rather, students were encouraged to use the tools opportunistically. Figs. 2–4 illustrate each tool. The students were encouraged to record their reflective thoughts regarding the use of the tools in Knowledge Forum.

2.2. Pedagogical designs for tool use

Principle-based, opportunistic, and adaptive use of assessment tools was fostered mainly by means of (1) teacher's encouragement to students to think about how to use the tools based on the principles; and (2) students' autonomous use of tools with reflection on the four questions—referred to as scaffolding questions—to be elaborated below. This approach contrasts with common computer-based assessment in which, rather than students requesting information on their own volition, they are presented with assessment results, prompts, and directives, which tend to convey that the computer is better able to direct their performance than they are (cf. Conole & Warburton, 2005; Thelwall, 2000). To address this issue, the design of the assessment tools and their use needs to raise awareness of knowledge building performance by giving students means to monitor their progress and take control of it. The tools should allow students to become more metacognitively aware of their ongoing knowledge work. That is the thrust of knowledge building principles—for example, *epistemic agency*, *collective responsibility for knowledge advancement*, *idea improvement*. The following four questions for reflection were recorded in a view in Knowledge Forum and students were encouraged to enter responses, in a further effort to support principle-based, active use of the analytic/assessment tools: (a) What information did you find useful from the tool and how will such information affect your knowledge building work? (b) What is your idea improvement this week? (c) What is your plan to advance your own knowledge work? (d) What is your plan to contribute knowledge to the whole class community? Of the four questions, the first question is directly related to the tool use, while the other three questions are more concerned with students' knowledge advancement activities with tool support. These questions were purposefully and collaboratively developed by the teacher and researchers based on the principles. In particular, the principle of "*concurrent, embedded, transformative assessment*" played a vital role in facilitating reflective, adaptive, and constructive rather than proceduralized use of these analytical tools.

2.3. Data source and analysis

Data were mainly collected from students' online discussion in Knowledge Forum. Multi-level content analyses (Miles & Huberman, 1994) allowed for exploration of content at multiple-grain sizes, to support different units of analysis. The research goal was to understand how principle-based use of knowledge-building analytic tools might affect student efforts to advance their community knowledge. If there was an effect, how and why did they proceed differently with the support of tools.

The purpose of multi-level analyses was to enhance the validity of analysis (Hogenraad, McKenzie, & Peladeau, 2003). This is also used as a means of addressing problems pertaining to the choice of single unit of analysis (see De Wever, Schellens, Valcke, & Van Keer, 2006, for a review). The first-level content analysis used key-terms excerpted from Knowledge Forum notes as the unit of analysis (see Berelson, 1952; Zolotkova & Teplovs, 2006). All key terms from each student's notes were extracted by means of the Semantic Overlap Tool. In addition, two researchers with a science teaching background independently examined this set of key terms and removed those unrelated to the field of inquiry. Key terms from the study of the human body from a biological perspective, Phase 1, included nerves and cells; key terms from the study of the human body from the physical perspective, Phase 2, included kinetic energy and momentum. Inter-rater agreement on selection of key terms was 0.95 after 30 unrelated key terms were removed, with differences resolved by discussion.

Keywords or key terms are commonly used for books or articles to produce subject indices and to facilitate idea searches. Keywords are also commonly used for knowledge or concept representation, such as propositional or semantic representations (see Anderson, 2000), tag clouds in websites (see Hassan-Montero & Herrero-Solana, 2006), and concept maps (see Novak, 2010). In the present study, we used unique key terms (extracted from each individual contributor) for individual knowledge representation (Hong & Scardamalia, 2014). In contrast, we used shared (overlapping) key terms that were extracted from the whole database for community knowledge representation (communal knowledge space). T-tests were computed to compare shared (i.e., overlapping) and unique contributions in the two phases (i.e., Phases 1 and 2) of the knowledge work advanced by students in the present study. The *idea diversity* principle can be reflected in the full set of unique and shared terms, and *symmetric knowledge advances* in changes over time.

The second-level content analysis used online discussion notes as the unit of analysis. The focus of analysis was on the descriptive statistics of student *collective responsibility for community knowledge* and *epistemic agency*. In particular, an open-coding approach (Strauss & Corbin, 1990) was employed (see Table 2). Two coders independently coded discussion notes and the inter-coder agreement was calculated to be 0.84, and differences were later resolved by discussion. Eight themes were identified from open coding, including (1) question-asking; (2) hypothesis generation and theorizing; (3) designing/conducting experiments, providing/gathering evidence; (4) finding references/solutions to questions; (5) planning/monitoring ongoing learning processes; (6) reflecting on what is learned; (7) reflecting on what should be learned; and (8) reflecting on

Table 2
Coding schemes for knowledge-building process and examples.

Main categories	Themes (and number of passages)	Examples
Self-initiated questioning and theorizing	Question asking (89)	How do cells move? I know that it moves through the flow of blood but how does it turn when the blood is not turning? Do cells have some sort of way of steering through the blood? (by JK)
	Hypothesizing/theorizing (134)	My theory is that putting your legs together helps because with your leg you can stretch further and you will have a better jump, because when you are at the end you will put your legs into a better jump position if your legs are together. (by CW)
Self-directed knowledge advancing activities	Finding references/solutions/answers (91)	In the reading my group did, we found out that a lymph node is really the size of a single kidney bean. We also found out that you can feel [it] in your lower neck. (by JB)
	Experimenting or providing/gathering evidence (29)	My evidence: We watched a video that explained that the skin was the first line of defense against viruses by not letting them in. Viruses can get in through your mouth, nose, an open cut on your skin, your eyes, and by a mosquito bite. (by JF)
	Planning/monitoring learning process (73)	My plan is going to reflect on what my data turns out to be. If my technique worked I'll try to long jump like that next time, if not I won't ever do that again. (by AW)
Self-assessing activities	Reflecting on what I have learned (56)	I learned that the pancreas is on the spine. And it helps you digest fat, proteins, and carbohydrates. The pancreas is behind the stomach; also the pancreas sends hormones and glucagons. The glucagons breakdown glycogen. (by MC)
	Reflecting on what I do not know or still need to know (30)	I want to know, if your cells are so well protected by your cell membrane deciding whether or not to let things in, how do diseases get through to infect your cells? (by SI)
	Reflecting on how to know better (44)	I learnt that I connected to fewer people in the human body database than the previous one. Maybe I should write a few more notes or build on to a few more people instead of just writing notes. (by TF)

how to advance knowledge. These themes were then further synthesized into three generic aspects of knowledge building, including: (a) self-initiated theorizing and questioning; (b) self-directed knowledge-advancement activities; and (3) self-assessment activities. These measures most directly tapped the following knowledge-building principles: *real ideas*, *authentic problems*; *improvable ideas*, *constructive use of authoritative resources*; and *rise above*. For example, students were directly engaged in addressing real-life problems by contributing new ideas (i.e., the first and second measures); they kept improving ideas by conducting experiments, (i.e., the third measure); they tried to maintain a critical stance when referring to and evaluating knowledge sources in order to advance knowledge (i.e., the fourth and fifth measures), and they work innovatively and reflectively with ideas to achieve higher-level understanding of problems and to go beyond best practice (i.e., the sixth, seventh, and eighth measures). The qualitative results were further quantified and statistically analyzed (Chi, 1997) using repeated-measures analysis to decide if there were any significant changes between students' Phase 1 and Phase 2 investigations.

The third-level content analysis examined students' responses to the guiding questions, identified above, employed to support principle-based tool use. The investigation used each student's complete response to a question as the unit of analysis for evaluating reflective aspects of that student's knowledge work–an analysis method based on Rourke and Anderson's (2004) account of the importance of developing a theoretically valid protocol. The principle of *rise above* and the conceptual definition of metacognition provided by Brown, Bransford, Ferrara, and Campione (1983) served as the assessment basis for this analysis, along with the overall guidance of the "*concurrent, embedded, and transformative assessment*" principle. Two coders independently evaluated all the student responses and assessed them as "*yes*", "*no*", or "*not applicable*", as elaborated in Table 3. Descriptive analysis was employed to compute percentages for each of the three categories. Inter-coder agreement was 0.91. All differences were resolved by discussion. Table 4 summarizes how the data collection and analyses are related to the above research questions.

3. Results and discussion

3.1. Key-term use

Key terms found in notes were identified as belonging to a student's personal repertoire when they were used (not simply read) by only that student; key terms were identified as belonging to the community when they were used by two or more community members. No significant differences were found in the mean number (M) of key terms used by each student personally, between Phase 1 and Phase 2 ($t = 2.07$, $df = 21$, $p > 0.05$). On average, each student contributed 40.10 key terms ($SD = 16.74$) in Phase 1 and 33.27 key terms ($SD = 11.35$) in Phase 2. In terms of the mean number of key terms overlapping in the community knowledge space, there was no significant difference between the two phases ($t = -0.62$, $df = 21$, $p > 0.05$; $M = 29.10$, $SD = 12.55$ in Phase 1, and $M = 30.64$, $SD = 9.35$ in Phase 2).

However, when looking beyond simple use/non-use of keywords–beyond one shared use to multiple shared uses – we find a different pattern. Analyses based on more than one shared term–on *frequency of use* of key terms—show a significant difference between the two phases ($t = -2.48$, $df = 21$, $p < 0.05$) in students' personal knowledge repertoire; mean frequency of use of key terms was 78.41 in Phase 1 ($SD = 38.74$) and 100.14 in Phase 2 ($SD = 40.11$). This indicates that key terms were more likely to be repeatedly used in Phase 2 as compared to Phase 1. Moreover, when examining the mean *frequency of use* of

Table 3
Protocol criteria for evaluating student responses to four questions.

Categories	Evaluation criteria
Awareness (Q1): What information did you find useful from the tool and how will such information affect your knowledge building work?	Yes □: The response conveys useful feedback for at least one of the three tools (i.e., Vocabulary Analyzer, Social Network tool, or Semantic tool). No □: No mention of useful feedback from any analytic tool N/A □: Neither of the above.
Evaluating/monitoring (Q2): What is your idea improvement this week?	Yes □: The response demonstrates that a student did evaluate his or her knowledge work for further improvement. No □: No evidence of any idea improvement mentioned in the response. N/A □: Neither of the above.
Planning for advancing personal knowledge (Q3): What is your plan to advance your own knowledge work?	Yes □: The response shows all of the following: (1) A feasible plan. (2) A plan carried out to completion and the plan advances personal knowledge relevant to the topic, i.e., long jump.* No □: The response shows one of the following: (1) No plan. (2) A plan, but not workable. (3) A workable but not completed plan. N/A □: Neither of the above.
Planning for advancing community knowledge (Q4): What is your plan to contribute knowledge to the whole class community?	Yes □: If a response shows all of the following: (1) A feasible plan. (2) A plan is carried out to completion for the purpose of community knowledge advancement.** No □: The response shows one of the following: (1) No plan. (2) A plan, but not workable. (3) A workable but not completed plan. N/A □: Neither of the above.

Note: * This was done by comparing the student's plan with his or her subsequent implementation, as reflected in the supporting data derived from (1) video recordings of individual long jump activities and (2) notes contributed later to the database. ** This was done by comparing the student's plan with his or her actual implementation as reported subsequently in notes contributed to the database.

overlapping or shared key terms in the community knowledge space, a significant difference was found between the two phases ($t = -7.69$, $df = 21$, $p < 0.001$). The second phase ($M = 324.36$, $SD = 68.0$) showed more shared terms used repeatedly by contributors than found in the first phase ($M = 203.77$, $SD = 63.77$). This suggests advances in *democratizing knowledge* (i.e., all participants are more likely to collaboratively make contributions to the shared goals of the community) and, successively, more *pervasive knowledge building* across phases and contexts. The findings indicate that principle-based tool support had a positive impact on facilitating students to pursue more integrative, depth-oriented knowledge building in Phase 2 (see Figs. 5 and 6).

Review of key terms showed that students were using sophisticated biological and physical concepts/terms to advance their knowledge work. For example, cell, white cell, blood cell, beta cell, T-cell, B-cell, and stem cell in Phase 1; kinetic energy, friction, acute angle, degree, linear, and momentum in Phase 2. As a student said after using the Semantic Overlap Tool to compare his own key-term use with the curriculum guideline for Grade 6: "What I learned from the [Semantic Overlap] tool is that I have written some really sophisticated words but the curriculum doesn't have them" (by JW). Fig. 7 further explores the relationships between the number of key terms and the frequency of key-term use in the two phases. In the figure the X axis represents the frequency of key-term use and the Y axis represents number of key terms. As it shows, a far greater number of key terms were used at a low frequency in Phase 1 than in Phase 2. For example, in terms of the frequency of key terms being used only one time, there were 183 in Phase 1 compared with 37 in Phase 2. And a far greater number of key terms were used at high frequency in Phase 2 compared to Phase 1. For example, there were three key terms that were used more than 100 times in Phase 2, but not in Phase 1. This suggests a change of *knowledge-building discourse* from more breadth-oriented inquiry in Phase 1 to more depth-oriented inquiry in Phase 2.

Using key terms (or keywords) for knowledge representation has limitations. One limitation is related to deficiencies in representing the process of collective knowledge building. As Ryle (1949) argued, knowing-that and knowing-how are two essential kinds of knowledge. Corresponding to a community's collaborative knowledge work, knowing-that represents the key ideas, concepts, and problems collectively employed or explored by the community members. Knowing-how represents the knowledge-building process through which members advance their understanding of these ideas or concepts. When these ideas or concepts are recorded in a communal database, key terms can serve as a useful tool in representing them. Nevertheless, they may not be as useful in capturing the knowledge building process, for instance, how certain key ideas or concepts are more deeply understood over time by community members. Moreover, knowledge representation using key terms may not elucidate "promising" ideas. Experts usually develop a strong sense of what is promising or problematic–ideas at the edge of their expertise. This represents a form of creative expertise that is essential to further extend their knowledge work and is evident in refinements that can better solve problems. To address these deficiencies, more sophisticated content analyses were conducted, as described below.

Table 4
Summary of research questions and corresponding data collection and analysis.

Research question	Data sources	Data analysis
Q1: Does principle-based tool use affect knowledge-building dynamics?	Key terms found in Knowledge Forum notes	T-tests to compare shared (i.e., overlapping) and unique contributions between Phase 1 and Phase 2
Q2: How is knowledge work altered with tool support?	Online discussion coded into three dimensions with eight different themes	Repeated-measures to identify significant changes between Phase 1 and Phase 2, three dimensions
Q3: Why do students employ different strategies with tool support?	Student responses to questions	Descriptive analysis to derive percentages of positive response to tool support in Phase 2

Note: Comparison between Phase 1 (no tools available) and Phase 2 (tools available) to uncover design effects of tool use.

3.2. Collective responsibility for community knowledge and epistemic agency

More in-depth content analyses were employed to understand how students took increasingly high levels of *epistemic agency* and *collective responsibility for community knowledge*. No significant difference between Phase 1 and Phase 2 ($t = 0.662$, $df = 21$, $p > 0.05$) in the total number of coded passages ($M = 13.55$, $SD = 6.22$ in Phase 1; and $M = 11.64$, $SD = 4.63$ in Phase 2) was found. Further analysis of complementary data using weekly videotaped observations in class confirmed that in both phases students were motivated and diligent in advancing their knowledge work.

Looking more closely at the knowledge-building components described above–(1) self-initiated activities (e.g., questioning and theorizing); (2) self-directed activities (e.g., designing/conducting experiments, providing/gathering evidence, finding references/solutions to questions), and (3) self-assessing activities (e.g., planning/monitoring ongoing learning processes)—differences were found. A repeated measures test indicated that there was an overall significant difference between Phase 1 and Phase 2 (Wilk's $\lambda = 0.22$, $F = 22.51$, $p < 0.001$, $\eta^2 = 0.78$), with interesting patterns suggesting different types of activities favored in Phase 1 and Phase 2. With respect to self-initiated activities, there were significantly more problems and hypotheses ($F_{(1,21)} = 34.13$, $p < 0.001$, $\eta^2 = 0.62$) generated in Phase 1 ($M = 8.09$, $SD = 4.01$) than in Phase 2 ($M = 3.90$, $SD = 2.22$). In terms of self-assessment activities, there were significantly more frequent assessment activities ($F_{(1,21)} = 17.60$, $p < 0.001$, $\eta^2 = 0.46$) in Phase 2 ($M = 5.00$, $SD = 3.10$) compared to Phase 1 ($M = 1.23$; $SD = 1.23$). There were no significant differences in self-directed activities, ($F_{(1,21)} = 1.02$, $p > 0.05$, $\eta^2 = 0.00$) between the two phases ($M = 4.23$ and $SD = 2.49$ in phase 1; $M = 3.55$ and $SD = 2.13$ in phase 2).

In interpreting results it is important to appreciate that students could use the analytic tools to reflect on their Phase 1 as well as Phase 2 knowledge building activities. This is because the tools, while only made available in Phase 2, could then be used to look back on Phase 1 activity. Accordingly students could see changes from Phase 1 to Phase 2. After using the Social Network tool, a student commented: "I have figured out that in the old view [i.e., a problem-solving space that was created in Phase 1] people have read each others' notes more times, but I haven't connected with one person as many times as the new view [i.e., a new problem-solving space in Phase 2]."

Overall results of self-initiated, self-directed and self-assessment activities suggest that support from analytic tools led to a shift from problem generation activities in Phase 1 to more self-assessment in Phase 2. This suggests a shift from focus on breadth of inquiry to more reflection and in-depth evaluation. However, while it is posited that increase in self assessment was due mainly to use of analytic tools, it could be due to other factors, such as questions that encouraged student reflection. We turn to a more detailed account of questions for reflection in the next section. To summarize, Fig. 8 shows the results for the three knowledge building aspects that support the above findings and interpretations.

3.3. Rise above and metacognitive work supported by use of analytic tools

The third-level content analysis examined student reflections entered into Knowledge Forum in response to questions posed by the teacher in Knowledge Forum. Descriptive analyses based on a protocol developed by Brown et al. (1983) were conducted. This analysis applied to Phase 2 because the tools were available only for this phase. It is important to note that students did not always record their reflections regarding analytic tools. The total number of reflective responses documented in Knowledge Forum notes was 135 ($M = 6.14$; per student $SD = 2.85$; with 26 responses for the first question, 43 for the second, 37 for the third, and 29 for the fourth), as elaborated below.

Awareness of effects of analytic tools (Q1): What information did you find useful from the tool and how will such information affect your knowledge building work? Of the 26 reflective responses, 24 (92.31%) indicated students were aware of benefits in the form of useful feedback for their knowledge work: (1) awareness of use of more advanced and difficult vocabulary, (Example #1: "The vocabulary [tool] … is good because you can see what you have typed that is advanced and misspelled!" by AW); (2) awareness of more opportunistic and dynamic collaborations (Example #2: "I really like the [social] network tool. I really enjoy finding out who I have connected with or talked to and who I should talk to more, to find out their theories," by AW); (3) awareness of overlap in key terms they used and uses by other members (Example #3: "… the [Semantic Overlap] tool can be helpful if you want to know how many words that you and someone else shared," by GW) and with those covered by the curriculum guideline (Example #4: "What I learned from the tool is that I have written some really sophisticated words but the curriculum doesn't have them," by JW). Taken together, the findings suggest that the tools

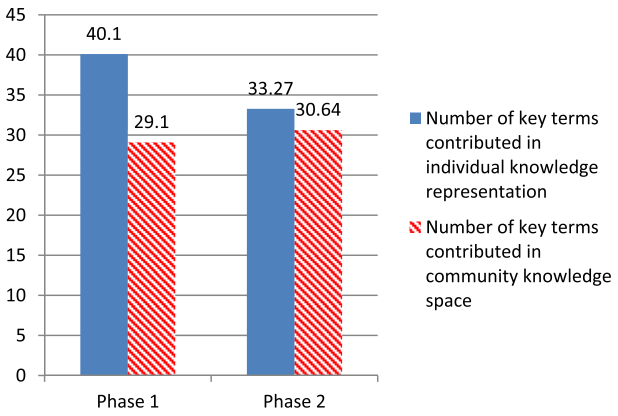

Fig. 5. Comparisons between Phase 1 and Phase 2 for key-term contribution (N = 22).

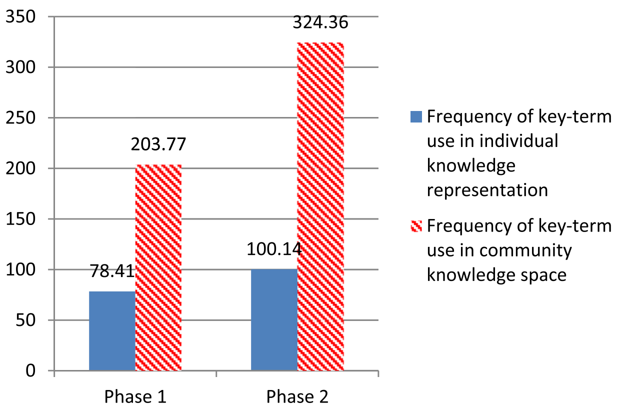

Fig. 6. Comparisons between Phase 1 and Phase 2 for frequency of key-term use (N = 22).

increased community awareness (particularly the Semantic Overlap Tool and the Social Network Tool, as suggested by the above Examples #2 and #3).

Evaluating/Monitoring (Q2): What is your idea improvement this week? Of the 43 reflective responses, 39 (90.7%) indicated that students monitored their own knowledge work for continual idea improvement (Example #5: "I figured out that putting your legs forward and swinging your body over your legs helps a lot," by JF). In addition, some responses demonstrated that students were able to monitor other students' knowledge-building progress by comparing each other's ideas (Example #6: "My idea for improvement early this week was: PUSH KNEES TO 45 DEGREE ANGLE. I tested it out and it really didn't work, although with M.C., whose long jump I have studied many times, it worked perfectly," by AH).

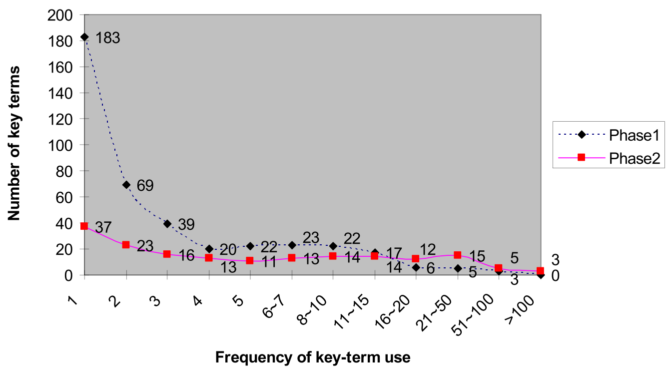

Fig. 7. Relationship between number of key terms and frequency of key-term use in the two phases.

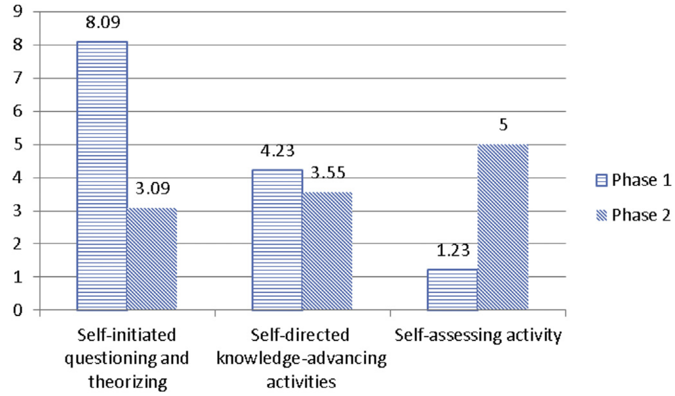

Fig. 8. Comparison between Phase 1 and Phase 2 in change in knowledge-building dynamics (Note: the number shown here are mean values).

Enhancing personal knowledge (Q3): What is your plan to advance your own knowledge work? Of the 37 reflective responses, 36 (97.30%) indicated that students generated and carried out feasible plans to advance their knowledge (e.g., Example #7: "I am going to get more interested [in] other people's theory," by GD; Example #8: "[S]ince my [previous] idea worked I will swing my arms up next time and tuck [myself] into a ball in the air," by PJ; Example #9: "My new plans are to try to get more height. And when I do my jump I will try to keep my legs together for the whole jump, 'cause on my jump I put my legs together for just the end, and not the whole jump so I don't know if it is better or not," by CW).

Planning—contributing to community knowledge (Q4): What is your plan to contribute knowledge to the whole class community? Of the 29 reflective responses, 28 (96.55) indicated that students were able to carry out feasible plans for the aim of community knowledge building (for instance, Example #10: "I will share this information by showing how far I got when I swung my arms up and then I will show how far I got when I tucked into a ball and swung my arms," by PJ; and Example #11: "My plan to give knowledge to the class is first I'm going to look at my data from my third jump. Then I'm going to write about it in Knowledge Forum so people won't have to try it again because I tried it," by JW).

Students' reflective comments suggest benefits of analytic tools, including collective awareness (Examples #2 and #3) and reflectivity (Example #7) in relation to community knowledge advancement. They indicate extension of socio-metacognitive capacity by enabling students to *rise above*—to reach a higher viewpoint for the realization of collective goals. For instance, students were able to reflect on their role in the community in relation to others through use of the Network tool and on contributions to the community in relation to sustained idea generation and improvement through use of Vocabulary and Semantic tools. Students identify ways in which their capacity has been extended through use of the analytic tools. Since they have had years of experience with Knowledge Building/Knowledge Forum in a school that engages them in knowledge building pedagogy and technology from the earliest years, it is worth note that they see clear advances attributable to the tools. So while there is no control group in this study it is reasonable to conclude that the tools are helpful, although there is a great deal to be learned regarding effective means of use.

4. Summary and conclusion

In summary, principle-based designs to foster more reflective and adaptive use of analytic tools for knowledge building enabled the pursuit of community knowledge as reflected in the following results: (1) Key-term use: Significant increases were found in the frequency with which key terms were used by individuals, in their own productive vocabulary as well as in the shared community space. More focused and sustained use of shared key terms created a more discursively connected community; (2) Knowledge building activities: rater evaluations of student notes showed a shift from problem generation and breadth of inquiry in Phase 1 to more self-assessment and reflection in Phase 2; and (3) Self-report of effects of analytic tools: Students were able to specify ways in which the analytic tools support their knowledge work, allowing them to monitor and evaluate ideas, to develop plans to advance their knowledge work based on greater understanding of contributions of others, to contribute to the class community rather than focus exclusively on their own work, and to be more self-directed in their knowledge work. Overall, principle-based use of knowledge building analytic tools, within a flexible design framework, enabled students to interpret feedback from analytic tools so that they could contribute more effectively to the community.

An important challenge this study addressed was use of tools not just for assessment but as knowledge-building tools, useable by young students. As suggested in the present study, principle-based design fosters a flexible, adaptive rather than step-by-step, procedure-based use of tools. Under these conditions Grade 5 and 6 students in the present study were able to productively incorporate assessment to advance community knowledge. Results suggest that improved individual knowledge growth was a by-product of more informed and productive social engagement.

While there was no control group in the current study, students reported an increment in their knowledge building capacity and attributed it directly to use of knowledge building analytic tools. This is impressive given that students in the present study had been using knowledge building pedagogy and Knowledge Forum for years (the school they attend uses this pedagogy starting in senior kindergarten). While they attributed advances to technological supports, advances are probably best accounted for by a combination of the tools and the reflective questions and school knowledge building environment that shaped tool use.

This research represents an effort to engage in sustained design research (Bereiter, 2004; Cobb, Confrey, DiSessa, Lehrer, & Schauble, 2003; Collins, Joseph, & Bielaczyc, 2004) aimed at the continual improvement of Knowledge Building and Knowledge Forum—an effort initiated three decades ago with CSILE–Computer Supported Intentional Learning Environments—the first generation of Knowledge Forum (Scardamalia & Bereiter, 1990). To continually improve the technology future research must address overall effects, as well as specific components (cf. Greller, Ebner, & Schön, 2014). In the present study it is impossible to tell how each tool contributed to the overall results; for example, perhaps the Semantic Overlap Tool alone contributed to increasing frequency of key-term use. Knowing the unique contribution of each tool to Knowledge Forum would be helpful for further improvement of the overall design environment as well as improvement of each tool.

While the major concern of this study was the social process of community knowledge building, rather than the psychological process of individual performance, it would be helpful to investigate individual processes–how tool use contributed to the increase of each student's community awareness and how such awareness influenced contributions to the community knowledge space. In terms of individual differences, which tools and/or tool functions are most frequently used, for what types of reflection (individual or social), by different students, and why? Further research is necessary and we recommend adding a tracking feature to Knowledge Forum to enable students' tool-use history to be automatically documented for more detailed analysis.

Principles are regarded as improvable objects in their own right, rather than a fixed set of parameters for principle-based design. While not investigated in the presented study, an important role for knowledge-building teachers as pedagogical designers is to treat principles as conceptual objects and to help improve them through a process of designing, improving, and re-designing theoretical designs in teaching practice (Bereiter, 2002)—what Bereiter and Scardamalia (2003) refer to as operating in “design mode.” Further research should also consider how teachers work innovatively in advancing both knowledge-building theory and practice.

In the present study, an attempt was made to use various key-term measures as a means of capturing and representing key concepts/ideas recorded in a community database. To further support community knowledge building, the research team has been working to improve the Semantic Overlap Tool. One possible improvement is to transform this tool into a key-term visualization tool to better represent content knowledge recorded in a community database, and to use key terms as hyperlinks to notes that contain these key terms. Such a design improvement might promote more interaction surrounding emergent ideas and opportunistic collaboration in creative knowledge work. Results confirm and extend results from other studies in which Knowledge Forum's analytic tools have been used to support formative evaluation conducted by students themselves, not by the teacher or technology (Resendes et al. in press). These tools give students new perspectives from which they can view their work. Rather than suggesting specific procedures, paths, or corrective tasks, the tools help students crisscross the landscape of their ideas (Scardamalia & Bereiter, in press). The fact that students can use these tools intentionally to contribute more to the community, and in the process advance their own knowledge, represents an important finding in the development of knowledge building analytics to foster group cognition (Stahl, 2006). The results further suggest the need for technology useable by young students to foster productive action and to uncover new competencies (Scardamalia, Bransford, Kozma, & Quellmalz, 2012).

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