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The Development of 21st Century Skills in the Knowledge Building Environment*

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Many of the most important problems facing engineers today have solutions that require not only technical expertise, but also the application of 21st century skills. Knowledge building (KB) is an instructional approach designed to support both deep learning and the development of these skills. In KB learners engage in a sustained discourse to share knowledge, formulate and refine inquiries, and continually improve their collective ideas and understanding of authentic problems. This paper presents an example of applying KB in an undergraduate engineering mechanics course. Data from 77 students engaging in KB and the discourse record of a KB team consisting of 8 students was examined to look for indications of 21st century skill development. Evidence was found supporting high-level creativity and innovation, communication, collaboration/teamwork, information literacy/research, critical thinking and metacognition skills. The discourse also provided evidence that the class was centered on the learner, knowledge, community, and assessment—all best practices for designing learning environments.

Keywords: knowledge building; 21st century skills; learning environment; assessment

1. Introduction

We are currently experiencing a shift from an industrial economy to a knowledge economy [1]. This transformation in how economies and societies function in the knowledge age requires important changes in how we educate engineers and a closer examination of the nature of knowledge. From the perspective of the learning sciences, "the meaning of 'knowing' has shifted from being able to remember and repeat information to being able to find and use it" [2]. Bereiter [3] notes that in the open informational world there is a plethora of information that contrasts with the closed informational world of traditional education. In this open world, more of the task of processing this information for quality and relevance, as well as building coherent knowledge out of bits of incoherent pieces of information, falls on the user. In a similar vein, Sawyer [4] writes that in the knowledge age the focus of education should not be on memorizing facts and procedures. Instead he emphasizes the need to develop integrated and usable knowledge with a deep understanding of complex concepts; the ability to work creatively with ideas to generate new theories, products, and knowledge; the skills to communicate and participate in discourse; and the capacity for lifelong learning.

The impact of the growing knowledge economy has resulted in a similar recognition by the engineering community of the need for developing new capabilities in engineering graduates (often referred to as 21st century skills). The National Science Board (NSB) [5] reported on the need to educate a different kind of engineer "with passion, some systems thinking, an ability to innovate, an ability to work in a multicultural environment, an ability to understand the business context of engineering, interdisciplinary skills, communication skills, leadership skills, an ability to adapt to changing conditions, and the eagerness for lifelong learning." The Accreditation Board for Engineering and Technology (ABET) [6] has similar expectations. In addition to the technical outcomes associated with applying math and science to solve problems, ABET also includes design thinking, multidisciplinary teamwork, problem formulation, professional and ethical responsibility, communication, an understanding of global and societal context, life-long learning and contemporary issues [7].

Compared to the dynamic economic and societal transformations brought on by the knowledge age, education structures have often remained comparatively unchanged [8]. In many educational settings students do not develop the ability to work with knowledge or to create new knowledge. For example, in engineering education it has been found that many students are unable to recognize the importance of innovation and the creation of knowledge in engineering design [9]. Students are often given the impression that knowledge is static and complete. As a result, many students become experts at consuming knowledge rather than producing knowledge [10]. There is a need for systematic education reform to "respond to and shape global trends in support of both economic and social development" [11].

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1.1 The need to assess transfer-in and transfer-out

The reasons why educational institutions are slow to respond to changing needs are varied and complicated. Despite the existence of much institutional and cultural drag, this paper will focus on examining how the current assessment measures are often misleading and therefore thwarting reform efforts. According to Schwartz, Bransford and Sears [12], assessments in many learning environments only measure what Broudy [13] refers to as replicative knowing (the ability to memorize sequestered facts and procedures) and applicative knowing (the ability to apply what has been learned to limited situations). Schwartz et al. [12] characterize these kinds of measures as "sequestered problem solving" (SPS) and note that these types of assessments measure *transfer-out.* In SPS assessments students cannot learn from their mistakes and there are no contaminating sources of information. Schwartz et al. contrast SPS assessments with Preparation for Future Learning (PFL) assessments. PFL assessments are designed to measure *transfer-in*. Their focus is on measuring what Broudy [13] refers to as interpretative knowing: the ability to ask good questions, seek out relevant information, make sense of a situation, and create new knowledge. In PFL assessments, students are asked to solve a problem that requires learning something new or seeing a situation from a different perspective. While SPS assessments focus on replicating information and procedures learned during instruction, PFL assessments are designed to assess how students think about and approach problems, particularly as they relate to the framing of unfamiliar problems that require new learning. These abilities are crucial to real-life problem solving and should be among the most essential outcomes of education [12].

Assessment "has a powerful effect on what students do and how they do it" [14], and it inevitably influences both teaching and learning. Engineering education—like many other fields—emphasizes SPS measures and the development of *efficiency* (rapid retrieval and application of knowledge to solve problems) needed for success in SPS assessments. Schwartz et al. [12] highlight the need to balance learning experiences designed to support efficiency with learning experiences designed to support *innovation* (opportunities for experimentation and deep learning). These innovation-learning experiences prepare students for success on PFL assessments. However, PFL assessments are rare in education compared to SPS assessments [12]. Because students often only acquire the information and operations that are required to complete a task [15], this scarcity of PFL assessments greatly impacts learning. In the current assessment and reward system, students receive the implicit message that to be successful in school it is best to direct their energy towards mastering efficiency—and not the innovation and experimentation that leads to deep learning and the development of 21st century skills.

1.2 Creating and assessing innovation through knowledge building

The *first goal* of this paper is to show an example of how the learning environment for an undergraduate engineering course can be recast as a knowledge building (KB) environment that balances innovation and efficiency. KB has an extensive research base [11, 16–21] and is the focus of a global network of organizations committed to the advancement of KB technology and practices in all sectors of society [22]. In many ways knowledge building resembles problem-based learning (PBL)—pedagogy more familiar to engineering educators. (See Prince and Felder [23] for a review of PBL in engineering education.) In both KB and PBL, students work together on ill-structured real world problems in which they identify on their own what needs to be found out, collaborate, distribute tasks, engage in dialog and focus on a cognitive outcome rather than an artifact or presentation. Through the process learners engage in analysis, evaluation and the creation of new knowledge—all higher order elements in learning taxonomies. Both approaches can be used successfully at any point in undergraduate education. However there are also important differences: KB problems are normally at the level of principles and are not cases; KB focuses more on understanding and idea improvement, rather than reaching a conclusion or practical result; KB problems are expected to undergo a transformation through the inquiry, resulting not in a problem being solved but instead in an advancement of the collective state; in addition to face-to-face interaction, much of the KB collaborative work is computer mediated and asynchronous; and the KB software environment often supports and structures the interactions [24].

At the heart of knowledge building is student participation in a recorded discourse in which they must improve their collective understanding by asking and refining questions, finding relevant authoritative sources, and synthesizing and growing their ideas to create new knowledge. Thus KB pedagogy not only emphasizes innovation, but through the recorded discourse that is part of the process it also provides a powerful PFL assessment tool. Thus the *second goal* of this paper is to examine this discourse and see if there is evidence of learning that an SPS assessment would not normally capture. Analyzing PFL assessments is inherently difficult, so the analysis will apply the work of Scardamalia, Bransford, Kozma and Quellmalz [11] connecting 21st century skills to characteristics of knowledge-creating organizations and see to what level these characteristics appear in the discourse.

2. Knowledge building pedagogy

Scardamalia and Bereiter [25] define KB as "the production and continual improvement of ideas of value to a community, through means that increase the likelihood that what the community accomplishes will be greater than the sum of individual contributions and part of broader cultural efforts." In KB students are expected to begin the transformation from being mere knowledge seekers to becoming competent knowledge workers who engage in the same social, intellectual, and discourse practices found in all knowledge producing organizations. A distinctive feature of KB is that it is idea-centered, a characteristic essential in a knowledge age pedagogy. By focusing on ideas rather than schoolwork and tasks, KB supports the intentional, reflective, and metacognitive engagement required for deep learning. ("Metacognition" is thinking about thinking—such as how to approach a learning task and self-monitoring progress toward its completion.) In a KB environment the focus of the learning community is on continually improving ideas. It begins with a question of understanding developed by the participants, such as "What if the world's water supply became measurably finite?" Participants are then encouraged to generate and post their ideas about the topic—typically in an asynchronous, online group workspace. In the process the community organizes itself into working groups that grow and change in response to the interests of the participants.

Through the KB process participants gain a deep insight into the ideas being improved in the discourse, and they learn how to be part of a mission-oriented team that solves problems and generates new knowledge [26]. Participants learn how to work in a completely unstructured environment in which they need to work together to create and answer their own questions, organize themselves, and evaluate their own progress. In the words of IDEO's Tim Brown, participants learn to "embrace the mess" [27]. Once participants develop KB competencies and "see themselves and their work as part of the civilization-wide effort to advance knowledge frontiers," they tend to adopt the KB method naturally in their thinking [28].

Providing ways for students to participate in discourse beyond the temporal and physical confines of the classroom has been shown to be valuable for supporting KB. To meet this need, Knowledge Forum (KF)—an online working environment designed to support asynchronous KB collaboration—has been developed [29]. In KF users can

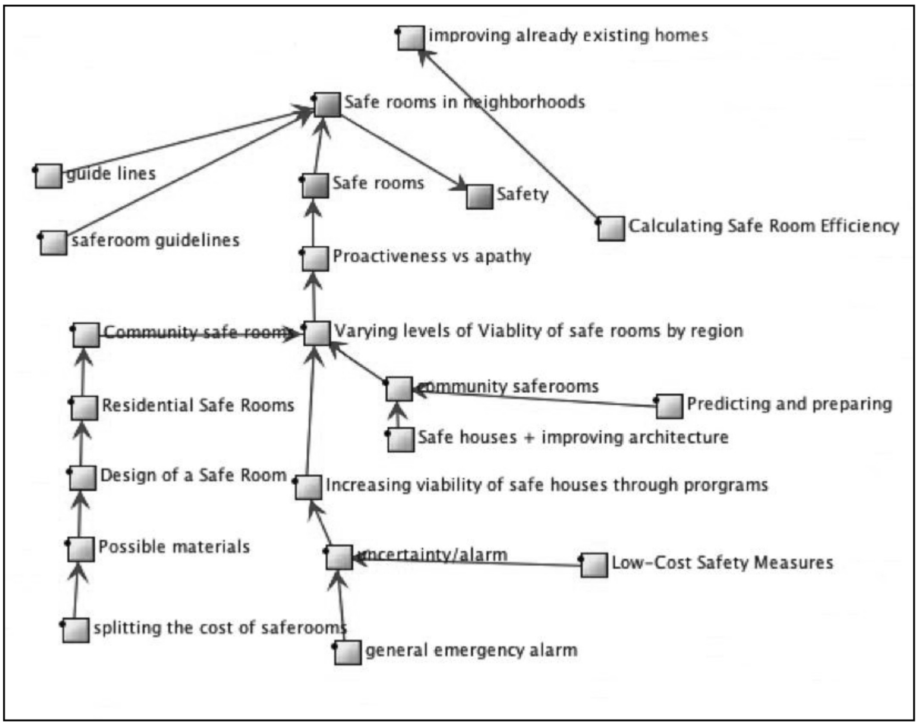

Fig. 1. Screenshot of part of a typical KF view. Boxes indicate notes that can be opened and read. Arrows indicate the direction of build-on.

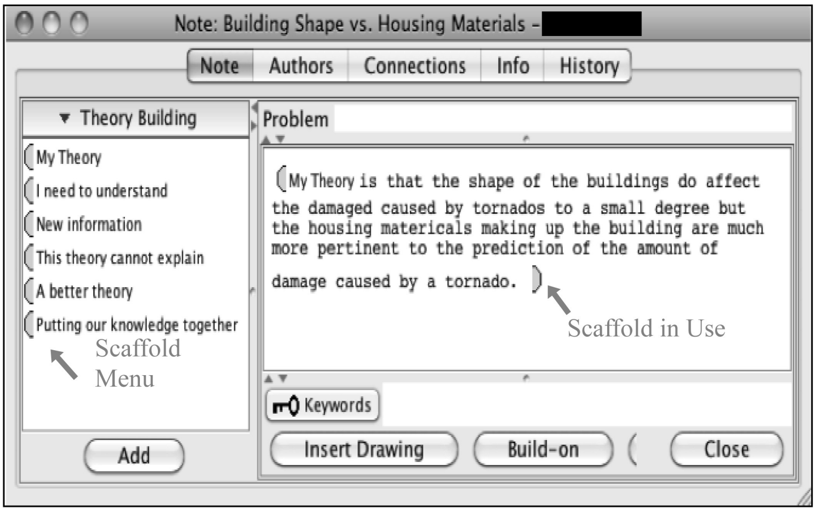

Fig. 2. Open note from the KF view shown in Fig. 1 (student name blacked out). This student used a theory-building scaffold to help structure the post.

contribute theories, working models, plans, evidence, data and other resources by posting *notes* to areas within KF called *views* that are accessible to all community members. Both notes and views are multimedia spaces, supporting text, graphics, and videos. Supportive features of KF allow users to build-on, co-author, and annotate notes of community members and to create reference links with citations to other notes. The users can organize their discourse by moving notes; adding graphics, pictures and texts; and creating new views. Fig. 1 shows a view in a KF workspace and Fig. 2 shows an example note.

A challenging aspect of implementing KB pedagogy in engineering education is that it is principle-based; that is, there are no guidelines or procedures for the instructor or student to follow. Instead KB implementation requires the instructor to understand KB theory and then to adaptively scaffold student learning as necessary to support the development of good KB discourse. In engineering only one example implementing KB has been published outside of those published by the authors. In this paper Mikic, Rudnitsky, Dewald and Desai [17] present an application of KB in a mechanics of materials class over a one- to two-week period. Consistent with KB theory, they cite that principles from Scardamalia [28], Scardamalia and Bereiter [25] and Dibartolo and Rudnitsky [30] guided the implementation. The twelve socio-cognitive determinants of KB discourse published by Scardamalia [28] are the most widely used principles in KB implementations. These principles include the need for real ideas and authentic problems; improvable ideas; idea diversity; rise aboves; epistemic agency; community knowledge and collective responsibility; democratizing knowledge; symmetric knowledge advancement; pervasive KB; constructive uses of authoritative sources; knowledge building discourse; and concurrent, embedded transformative assessment. Ellis et al. [21] identify key issues for the instructor to consider when implementing KB principles in undergraduate engineering education. They include: (1) creating student engagement around KB questions; (2) establishing, adjusting and supporting KB participant structures; and (3) assessing whether students are using knowledge in innovative ways.

3. What knowledge building looks like in the classroom

The authors have published three different examples of applying KB in undergraduate engineering. Included are applications in artificial intelligence [21], geotechnical engineering [20] and introductory engineering mechanics [18–19]. These studies found the following:

- In each KB application ideas were improved; questions were redefined; authoritative sources were used constructively; diverse ideas were raised; higher level concepts were created; and students developed their own approaches to advance the discourse [18–21].
- Although much time inside and outside of class was redirected from efficiency to innovation, SPS assessments measuring efficiency either did not change significantly [19] or improved [20] with KB implementation.
- Most students found that the collaborative aspect of KB and the exposure to a wide range of ideas differentiated it from other classroom activities; viewed KB positively because of the opportunity

to share ideas with their classmates, to think about issues and respond at their leisure and a variety of other reasons; and believed that KB helped prepare them for participating in knowledge organizations [20–21].

- Student concerns about publicly sharing their ideas were effectively addressed through KB Talk. In KB Talk the instructor meets with each KB team to help them begin a discourse (discourse about the discourse) to self-monitor and reflect upon their progress [18, 21].
- Student conceptualization of learning became significantly more learner-centered in KB classes [18].
- Questions became more explanatory and statements became more focused on theory building throughout the semester [18].

This paper focuses on analyzing the discourse recorded in an introductory engineering mechanics class because it is the most advanced application of KB pedagogy, produced the largest dataset, and is a subject area commonly taught in engineering. A summary of the application will be presented first, followed by the analysis.

3.1 Learning environment and participants

KB was implemented in introductory engineering mechanics (EGR 270) in 2011 (44 participants) and 2012 (34 participants). EGR 270 is a four-credit, semester-long introductory engineering mechanics course offered at Smith College. Because Smith College is a women's college that allows cross-registration from nearby co-ed colleges, the participants included 76 females and one male. Almost all students in EGR 270 were sophomores majoring in engineering science and none had prior KB experience. The course met twice per week for 80 minutes and once per week for a 170-minute laboratory. The following were the intended learning outcomes:

- Develop an efficient command of the basic information, procedures and methodology needed to understand the mechanical behavior of an object under loading.
- Develop the ability to use knowledge in innovative ways.
- Improve competencies needed to participate in a knowledge organization.

Mechanics concepts included an introduction to stress and strain, 2-d and 3-d rigid body equilibrium, frames and machines, centroids, moment of inertia, and shear and bending moment diagrams. A variety of strategies were used to balance efficiency and innovation in the classroom. These included lecture, discussion, hands-on activities, group problem solving, case studies and laboratories. Traditional efficiency-oriented aspects of the course—including labs, homework, and in-class examples—were designed to integrate the KB themes. For example, the importance of hurricane straps for protecting a mobile home in high winds was used to illustrate 2-d static equilibrium. SPS assessments (mainly exams) retained the same range and depth of mechanics content they had before KB was included in the course.

3.2 Context for knowledge building inquiry

The initial context for KB focused on understanding how an EF-3 tornado damaged buildings and affected neighborhoods near Smith College. KB seeding included a site investigation of impacted neighborhoods and meetings with their residents. Students then collaborated to develop KB questions; form groups around each of these questions; explore and refine their ideas; and improve their initial questions. The instructor did not participate in the discourse, but instead supported KB through initiating a metadiscourse with each group.

3.3 Classroom implementation

Metacognitive activities enhance learning, but metacognitive thinking is not spontaneous. Thus it is important to incorporate metacognitive support in the design of the learning environments [31]. In EGR 270 the concept of metadiscourse (discourse about the discourse) was introduced through weekly KB group meetings with the instructor early in the semester. These KB Talks were designed to help students reflect upon the learning process; increase student agency and risk-taking; and improve the progress and quality of the KB discourse. The instructor initially facilitated these meetings by modeling metadiscourse questions (such as asking about the current question, progress, challenges, knowledge gaps, next steps, etc.) and initiating discussion on KB principles (such as the proper use of authoritative resources and the need to "rise above" the discourse) when the need became apparent in the discourse. Later in the semester these meetings became fully student-driven as students learned to organize themselves, reflect upon the advancement of their ideas, and take action to increase their progress.

In addition to the KB Talks that took place within a group, the instructor also organized a formal discourse among the groups in which ideas were shared. In this *jigsaw* approach, students first met with their own KB groups to summarize key points in their own discourse before splitting up and forming new heterogeneous groups (i.e. each new group consisted of one member from each KB group). In these heterogeneous groups students both shared what they had learned and worked together to answer discussion questions from a list posed by the instructor. These questions addressed themes that ran through many of the group discourses. Finally, the students returned to their original KB groups to discuss the new ideas that arose from their discussions and how these ideas fit into their KB discourse.

3.4 Grading

KB counted for 25% of the EGR 270 course grade. The quantity of student contributions (as measured by notes posted and notes read using the Knowledge Forum analytic tool kit) counted for 5%. The quality of student contributions (as judged by the instructor) counted for 10%. Finally, a reflective student essay (adapted from Lee, Chan and Aalst [32]) counted for 10%. In this essay students reflected on how ideas in the discourse changed; selected important notes and discussed how they contributed to idea improvement and their own learning; and reflected on how their observations had changed when watching a tornado impact a building.

4. Assessing student learning

KB pedagogy can potentially transform learning environments. However, its benefits may not be recognized if student learning is only assessed through traditional SPS measures, such as exams with well-defined problems. Although more difficult to apply, PFL measures are essential for assessing KB's effectiveness. The KB discourse recorded in Knowledge Forum meets the criteria for being a PFL measurement because it provides insights into how learners think about, approach and frame unfamiliar problems that require new learning. The challenge lies in how to analyze this discourse and measure student achievement in a way that is useful outside of the KB research community.

4.1 Using 21st century skills as a PFL metric

In order for learners to develop the capacity to actively engage in innovation work, schools need to prepare students to participate in sophisticated thinking and flexible problem solving with strong collaboration, communication, and leadership skills—all of which are captured by the 21st century skills [33]. Because these skills are consistent with the goals of KB and are widely cited in a variety of disciplines and contexts, they are an ideal metric for evaluating student participation in KB. Scardamalia, Bransford, Kozma and Quellmalz [11] have created a developmental framework for analyzing learning environments in the context of 21st century skills (the framework is presented in Table 1 in Section 6). For each 21st century skill, they cite *entry-level* characteristics that may be expected of students who have had no prior engagement in knowledge creation and *high-level* characteristics describing capable participants in a knowledge-creating enterprise. They describe these characteristics as "a developmental trajectory from active or constructivist learning as the entry point, to complex systems of interactivity and knowledge work that enable the generation of new knowledge, the capacity to exceed standards, and the drive to go beyond best practice at the high end." These characteristics are used in this study to assess the KB discourse created in EGR 270.

5. Analyzing KB discourse using 21st century skills

Over one thousand notes were posted each year in EGR 270. Most were significantly longer than the example shown in Fig. 2. Therefore in this study only one group was selected for the analysis. Labeled Group 5, this group of eight students was chosen because they initially struggled early in the semester but then improved to become successful by the end of the semester. Group 5 posted 338 notes starting with the following note co-authored by the entire group that stated their initial KB question (< > indicates a scaffold):

> <I need to understand> what precautions were incorporated into the infrastructure design and building codes in preparation for tornadoes and how will this event change them?

Each note posted in Knowledge Forum by Group 5 was examined for evidence of 21st century skill characteristics. Based upon the work of Chuy, Zhang, Resendes, Scardamalia and Bereiter [34], each note was also categorized with 84% inter-rater reliability into the following contribution types: factual questions, facts, explanatory questions, synthesizing, epistemic agency, working with evidence, support, theorizing and strategic talk. This classification is also used in identifying 21st skill characteristics in the discourse. Table 1 shows, for each skill, the characteristics described by Scardamalia et al. [11] and observations citing evidence related to their development in EGR 270 through KB.

6. Discussion

Knowledge building represents a promising approach for enhancing engineering education in a way that supports deep learning and the development of 21st century skills through discourse. Because this discourse is recorded in Knowledge Forum, it can also serve as an excellent PFL formative and summative assessment tool. Scardamalia et al. [11] write about the need for such tools in

Table 1. Evidence Supporting the Development of 21st Century Skills in EGR 270

21st Century Skill	**Characteristics**	**Observations**
Creativity and Innovation	Entry-level: Internalize given information; beliefs/ actions based in the assumption that someone else has the answer or knows the truth. High-level: Work in unsolved problems; generate theories and models, take risks, etc.; pursue promising ideas and plans.	Notes categorized as factual questions decreased significantly from 13% of the Group 5 notes in the first half of the semester to 2% in the second half (p-value < 0.0001). Similarly, notes focusing on facts decreased significantly from 25% to 6% (p-value < 0.0001). Example of a question from early in the semester: *My question is: how do we get a hold of these building codes? Are they open to the public, and who is in charge of them?* Example of a question from later in the semester: *<I need to understand> how to optimize the safety measures so that houses are reasonably safe without being too expensive for people to buy.* Not only did questions improve, but the discourse showed a emerging capability to work on unsolved problems; develop theories (63 notes included theories); form hypotheses; and collaborate to decide on the most promising ones to explore.
Communication	Entry-level: Social chit chat; discourse that aims to get everyone to some predetermined point; limited context for peer-to-peer or extended interaction. High-level: Discourse aimed at advancing the state of the field and at achieving a more inclusive, higher order analysis; open community knowledge spaces encourage peer-to-peer and extended interactions.	Although no groups engaged in social chit chat, many notes early in the semester were task-oriented and not directly related to ideas and innovation. However, from the first to second half of the semester task-oriented notes decreased significantly from 13% to 3% of the total notes (p-value < 0.0001). Over the same time period theory-generating and synthesizing notes—indicative of high-level communication skill—increased significantly from 11% to 27% (p-value < 0.0001).
Collaboration/ Teamwork	Entry-level: Small group work: divided responsibility to create a finished product; the whole is the sum of its parts, not greater than that sum. High-level: Shared intelligence emerges from collaboration and competition and enhances existing knowledge. Individuals interact productively and work with networked ICT. Advances in community's knowledge and prized over individual success, while enabling each participant to contribute.	Early in the semester: The group divided into subgroups with separate views and assigned individuals responsibility for topics such as socio-economic issues; building codes; and enhancing building component safety. Later in the semester: The group collaborated to create new knowledge that went well beyond the simple accumulation of facts. For example, a new view included a discussion that summarized and synthesized the group's findings.
Information Literacy/ Research	Entry-level: Inquiry: question-answer, through finding and compiling information; variable testing research High-level: Going beyond given information; expansion of social pool of improvable ideas, with research integral to efforts to advance knowledge	Early in the semester all notes were entry-level. For example: *I found a few movies. I think the national geographic one is especially good! [URL followed]* In mid-semester the group formulated a policy that all notes citing authoritative sources must include a short summary of its content. For example: *Hey guys, I found this video that I think is interesting. It explains what a tornado proof house is, and questions if there really is a tornado proof house. Here's the link. [URL followed]* Later, they improved their policy by requiring an explanation of how the authoritative source can be applied to improve the group's ideas. This new policy resulted in notes that included analysis, original theories, and knowledge advancement. For example: *<My Theory> is that there is some way of preparing a home for a tornado that is effective in protecting the occupants, but not too costly. <New information>: this website [URL included] makes me think that an in-residence shelter might be the most efficient way to protect a house from a tornado . . .*
Critical Thinking, Problem Solving and Decision-Making	Entry-level: Meaningful activities are designed by the director, teacher or curriculum designer; learners work on predetermined tasks set by others. High-level: High-level thinking skills exercised in authentic knowledge work; the bar for accomplishments is continually raised by participants as they engage in complex problems and systems thinking.	Early in the Semester: A few students embraced the opportunity to develop, explore and improve questions that interested them, but most looked to the instructor for permission, guidance and approval. For example, early in the semester during KB Talk the group expressed frustration that they were "stuck" with their original question. Later in the Semester: Students increasingly took ownership of knowledge advancement. For example, after reflecting on why their initial question was not productive and why they did not feel empowered to improve it, the group continuously improved their questions throughout the rest of the semester.

Table 1. (*continued.*)

21st Century Skill	Characteristics	Observations
Citizenship—Local and Global	Entry-level: Support of organization and community behavioral norms; "doing one's best"; personal rights. High-level: Citizens feel part of a knowledge-creating civilization and contribute to a global enterprise; team members value diverse perspectives, build shared knowledge in formal and informal settings, exercise leadership, and support inclusive rights.	Many notes showed students engaging with citizenship skills and these notes often prompted further group discussion. Two excerpts include: *Meanwhile many people still can't return to their homes, three months after the fact, because of insurance policies.* *It was really interesting to see the human/community context of the disaster. It makes me feel a lot more involved.* A variety of evidence indicates that team members valued diverse perspectives. Every group member posted a note that led to a major discussion building on their note and 10% of the group's notes supported opinions of other group members.
Life and Career Skills	Entry-level: Personal career goals consistent with individual characteristics; realistic assessment of requirements and probabilities of achieving career goals High-level: Engagement in continuous, "lifelong" and "life-wide" learning opportunities; self-identification as a knowledge creator, regardless of life circumstance or context	A willingness to engage in "lifelong" learning was demonstrated in the student reflection essays required at the end of the semester. One student wrote, *Using knowledge building has also improved my self-motivation to understand a problem on my own, using what is covered in class as tools, and mostly ask myself what I would need to [develop] a better understanding.* An analysis of the essays showed that: 24% wrote that they learned how to discover their own way of learning; 70% wrote that KB shaped their thinking and helped them find a way to approach a problem; and 54% wrote that KB allowed them to explore a question from different perspectives.
Learning to Learn/ Metacognition	Entry-level: Students and workers provide input to the organization, but the high-level processes are under the control of someone else High-level: Students are workers who are able to take charge at the highest, executive levels; assessment is integral to the operation of the organization, requiring social as well as individual metacognition	Instructor records of the KB Talk discourse support the development of high-level skill. For example, the group recognized the need to self-assess and decided to create a metadiscourse view. They posted 44 notes in this view that assessed the discourse, the functioning of the group, and contributions of group members. In one note a student discussed the importance of building off and challenging ideas to reach higher levels of understanding: *. . .In order for this to truly work we must all contribute not only individually but collaboratively which requires not only reading other's postings but offering our own input as well in order to build off of their ideas and allow us all to get to a higher level of understanding and education that could only be achieved by gathering our knowledge together. While conformation and agreement is good to receive from others, it is also beneficial to counter someone or offer a new idea or direction . . . I feel that in order to really begin to advance toward our goal we must all put as much time into building off of other's posts as we do to writing our own.* End of the semester surveys in 2010 and 2011 also support the transfer of responsibility from instructor to student. Both years were taught by the same instructor—the only change in 2011 was the addition of KB. Students answered the question, "What is the role and responsibility of the teacher in advancing knowledge in this class?" Student responses categorized as "explain things clearly" dropped significantly from 27.6% to 4.1% (p-value < 0.007) from 2010 to 2011, while responses categorized as "guide students to self-direct their learning" increased significantly from 3.5% to 20.3% (p-value < 0.030).

measuring 21st century skills. For example, they write that measuring how far learners go beyond the specifications of the learning activities—an approach that can be difficult to implement in a traditional classroom—may assess creativity and innovation. In another example they note that collaboration with peers and experts can be assessed by monitoring the formation of groups, as well as through the metadiscourse that reflects on the group processes and progress towards achieving goals. This again can be difficult to implement in a traditional classroom.

Another advantage of KB is that 21st century skills are learned in an integrated context that is more like knowledge-creating organizations than traditional classrooms. Scardamalia et al. [11] write that 21st century skills are often treated separately in schools with each one having a separate learning progression, curriculum, and assessment. In contrast, in the EGR 270 KB learning environment the skills are completely intertwined.

Knowledge building is also consistent with best practices for designing classroom environments. It includes all of the four important attributes cited in *How People Learn* [2] for designing effective classroom environments—learner-centered, knowledge-centered, community-centered and assessment-centered.

6.1 Learner-centered

In learner-centered classrooms, student interests, attitudes and beliefs are addressed and valued. Teachers try to tap into students' prior knowledge and students have some decision-making power about what they will learn. The development of several 21st century skills (such as critical thinking and learning to learn) requires a learner-centered classroom. Properly implemented KB is learner-centered and evidence supports that this happened in EGR 270. This evidence includes: (1) the KB discourse, (2) observations of KB groups and (3) student surveys.

The KB discourse showed that student groups formulated their own questions; decided how to engage together in KB; and self-assessed their progress through metadiscourse. Observations of the KB groups showed that the metadiscourse was oral as well as written and that students connected KB to their own lives and interests. Table 1 (section on Learning to Learn/Metadiscourse) shows that including KB changes the way students view the role of the instructor. Consistent with a teacher-centered, transmission model of learning, they viewed the role of the instructor as explaining things clearly before KB was implemented in the class. After KB was implemented they viewed the instructor as more of a coach who helped students self-direct their learning.

Including KB also impacted the more traditional aspects of the class that focused on procedural knowledge and made them more learner-centered. Reading the KB discourse helped the instructor better understand the preconceptions, theories and interests that each student brought to the class. With this information he was able to make explicit connections in lectures and labs between mechanics concepts and the students' KB discourse. The instructor also found in the KB discourse a supply of real problems encountered by students that could be used as lecture examples. These problems not only better engaged students in learning problem-solving procedures but also provided meaningful, authentic opportunities to focus on theory limitations and applicability.

6.2 Knowledge-centered

Knowledge-centered learning environments are essential for supporting the development of 21st century skills. These environments emphasize deep learning over rote learning; teach metacognitive strategies; and favor doing with understanding over hands-on doing [2]. Evidence supports that KB is a knowledge-centered pedagogy. Table 1 (section on Creativity and Innovation) shows that students engaged increasingly in deep learning as they changed their initial focus from asking factual questions to asking questions requiring explanations. With this change students increasingly took risks to develop and improve their theories. Through KB Talk they were introduced to metacognitive strategies and practiced metadiscourse with the instructor. This led to groups beginning their own metadiscourse that included self-assessment, reflection, and goal setting.

6.3 Community-centered

Community-centered learning environments encourage interactions between individuals in the community and also support participants in connecting with and exploring the world with a collective spirit. Being community-centered is essential for developing 21st skills—particularly communication, citizenship and collaboration/teamwork. As evidenced by the number of notes posted in the KB discourse, student interaction was encouraged in EGR 270. The participation level of Group 5 was typical and resulted in 338 notes. While individuals posted most notes, multiple authors collectively posted others (particularly rise aboves). Very few notes were left standing alone in the workspace; almost all notes built on another note, were built on themselves, or both. Knowledge Forum analytics showed that almost all notes were read (or at least opened) by all members of Group 5; this was also true for other groups.

In traditional engineering mechanics classes, students have little opportunity to connect to the outside community. As Bereiter points out, "schools are uniquely ill-suited for it because of their isolation from real-world problems" [35]. By contrast, KB not only supports collaboration among students, but also encourages engagement with the larger community through engaging with real problems. For example, Group 5 brought numerous authoritative sources into the discourse, including research articles, news articles, and videos. They also interviewed civil engineers and citizens from communities impacted by the tornado.

6.4 Assessment-centered

The fourth attribute of an effective learning environment is being assessment-centered. "The key principles of assessment are that they should provide opportunities for feedback and revision and that what is assessed must be congruent with one's learning goals" [2]. EGR 270 is unusual in that it balances SPS and PFL assessment. Exams, homework and lab reports provide traditional SPS measures of replicative and applicative knowing. The evaluation of KB participation used in the class (described in Section 3.4) is largely a PFL assessment and measures interpretive understanding by measuring how well students develop good questions, seek out relevant information, make sense of a situation, and create new knowledge. These assessments are consistent with the course learning goals. The KB discourse recorded in Knowledge Forum is also an important formative assessment tool and serves to make the student thinking process visible at all times to both students and the instructor. This allows students to receive real-time feedback on their ideas from their peers through the discourse and from their instructor through KB Talk meetings or individually.

7. Conclusions

This paper presents an example of applying KB in an undergraduate engineering mechanics class. An analysis of the KB discourse using a developmental framework designed to analyze learning environments in the context of 21st century skills supports their development throughout the semester. Evidence points to the development of the following high-level 21st century skills characteristics throughout the semester:

- Creativity and innovation—the percentage of notes focused on facts decreased and students showed an increased capacity to develop theories and collaborate on unsolved problems;
- Communication—the percentage of task-oriented notes decreased and the percentages of theory-generating and synthesizing notes increased;
- Collaboration/teamwork—the group behavior changed from dividing up work to collaborating;
- Information literacy/research—the introduction of authoritative sources into KB discourse changed from just sharing to analysis that supports knowledge advancement;
- Critical thinking—students showed increased agency and ownership of knowledge advancement; and
- Learning to learn/metacognition—students initiated a group metadiscourse and their conceptualization of the learning process became more learner-centered.

Finally, evidence supports the application of KB as being centered on the learner, knowledge, community and assessment—all best practices for designing classroom environments.

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