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Putting more 'modern' in modern physics education: a Knowledge Building approach using student questions and ideas about the universe

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Abstract

Student-generated questions and ideas about our universe are the start of a rich and highly motivating learning environment. Using their curiosity-driven questions and ideas, students form Knowledge Building groups or 'communities' where they plan, set goals, design questions for research, and assess the progress of their work, tasks that were once under the control of the teacher. With the understanding that all knowledge and ideas are treated as improvable, students work collaboratively at their level of competency to share their knowledge, ideas and understandings gained from authoritative sources and laboratory activities. Over time, students work collectively to improve the knowledge and ideas of others that result in advances in understanding that benefit not only the individual but the community as a whole.

Learning outcomes reported in this paper demonstrate that a Knowledge Building environment applied to introductory cosmology produced similar gains in knowledge and understanding surrounding foundational concepts compared to teacher-centred learning environments. Aside from new knowledge and understanding, students develop important skills and competencies such as question-asking, idea development, communication, collaboration that are becoming ever more important for 21st century living and working. Finally, the process of planning and initiating a Knowledge Building environment that produced the results reported in this paper is outlined.

Introduction

During the past several decades, exciting breakthroughs in physics have further developed our understanding of the universe. Whether it is moving quantum information using teleportation [1], the effects of dark energy upon the expansion of the universe [2], or more recently, direct observation of gravitational waves produced by two colliding black holes [3], these discoveries at the frontiers of modern physics never fail to fascinate us. But in our schools much of the modern physics curriculum formally bypasses these and other exciting discoveries, focusing on discoveries primarily from the early 20th century.

This paper seeks to demonstrate how cutting-edge discoveries such as those described above can find a place in our classrooms. By using an open-inquiry learning environment called Knowledge Building, students practice the processes of science—collaboration, communication, curiosity, and creativity—that support learning of 21st century modern physics at their level of competency.

What is Knowledge Building?

Knowledge Building is a term used to identify 'any environment (virtual or otherwise) that enhances collaborative efforts to create and continually improve ideas' [4]. Creating and improving ideas drives technological and scientific change. Idea improvement is a term that means taking a physical object or a mental model and building upon it with new knowledge resulting in a product that becomes more useful to more people. In fact, throughout human history just about every physical object or mental model identified has been improved upon often through social and collaborative engagement. For example, during the past decade new ideas related to cell phone technology have resulted in continual improvement in terms of its size, speed and functionality. Scientific models undergo idea improvement as well. Newton's model of gravitation was improved upon by Einstein's idea that gravitation is actually a distortion of space and time caused by mass and energy. Furthermore, the model of the atom has undergone several improvements over the last two centuries, each improvement helping to explain experimental observations that the older model could not. Idea improvement is never a one-time event. Instead, it is a continuous process that builds upon the previous knowledge and ideas of others. The fact that idea improvement is so pervasive in the world beyond the classroom suggests that more attention to this process is worth examining as a pedagogical component in our classroom practices.

Theoretical foundations for Knowledge Building

In Knowledge Building (KB), students work collaboratively with authentic problems using technology to aid in collaboration and investigation. The goal is to produce knowledge and ideas that demonstrate an understanding or resolution toward their problem. This approach has similarities to other open-inquiry models such as Problem-Based Learning [5], Project-Based Learning [6], and Group Investigation [7]. What separates KB from those open-inquiry models is its insistence that all knowledge and ideas are treated as improvable. This is similar to processes associated with scientists working at the frontiers of their disciplines. They are constantly asking questions, producing new ideas and building upon the ideas of others that drive understanding to ever deeper levels. The final product of a KB activity is often a conceptual product that demonstrates how new knowledge and ideas were used to advance understanding at addressing authentic problems.

To facilitate the process of KB, a set of twelve principles was developed by Scardamalia [8] that characterize how students might work with knowledge and ideas in ways that mirror the knowledge work of scientific and technological organizations. Table 1 outlines several of the core principles. When students form like-minded groups or 'communities' to engage with authentic, real-world problems, they design important questions based on what they need to know to help understand the scope of their problem. Students assume a collective responsibility to produce and refine knowledge surrounding their problem with the understanding that improving upon the knowledge of others is an important outcome. In essence, students form a 'collective intelligence' where the outcome of working collaboratively with a problem would be superior to that of working alone.

Knowledge Building in the physics classroom

This section demonstrates the application of the KB principles to the classroom in the topic of modern physics. It outlines a five-stage procedural approach for planning and implementing KB that produced the results reported later in this paper. The asynchronous nature of KB facilitated by the use of computer technology allows the activity to take place at times most convenient for teacher and student. Hence, the timing for the implementation of a KB activity can last anywhere from several weeks to several months depending upon the desired depth of the topic to be investigated.

Table 1. Several core principles of Knowledge Building.

Key principles	Explanation
Real ideas, authentic problems	Students work with problems they really care about in an effort to understand their world
Improvable Ideas	Students treat all ideas as improvable. Students work continuously to improve the quality and coherence of knowledge and ideas that result in continuously deeper learning gains
Epistemic agency	Students take charge in defining problems to study, plan and set goals, self-motivate, and assess their progress
Community knowledge, collective responsibility	Students understand that working as a community toward shared goals is valued more than individual achievement. Students share responsibility in improving knowledge and ideas that benefit the entire community

Stage 1: Selecting a Knowledge Building Topic

Quantum foundations, cosmology (e.g. black holes, the big bang, dark energy, and dark matter), and particle physics are ideal topics for KB work. They spark the imagination, create wonderment and generate questions in both students and adults alike. If possible, giving students a choice in which topic to explore will heighten intrinsic motivation resulting in a greater investment in time and energy learning about their topic.

Stage 2: Fostering the Development of Questions and Ideas

Step 1. Once the topic has been selected, the teacher designs a ‘hook’ in order to gain student attention and promote interest [9]. The hook may consist of a news story, a thought-provoking question, guest speaker, field trip or high quality video. Using high quality video found on the Web is likely the easiest and most convenient way to provide a hook on those topics outlined in Stage 1.

Step 2. Prepare students that they will be asked to develop effective questions about the topic under investigation at the conclusion of the hook. It has been my experience that students often struggle initially to develop questions that have meaningful depth to them. This is likely due to the fact that they rarely practice this skill in today’s formal schools [10].

To help students develop effective questions, begin by introducing students to the difference between open-ended and closed-ended questions [11]. Closed-ended questions are often fact-based that usually ask for simple information (e.g. ‘How old is the universe?’). Open-ended questions lend themselves to explanation-based responses (e.g. ‘How do we know how old the universe is?’). Although closed-ended questions develop important factual knowledge of concepts, open-ended questions develop knowledge about relationships between concepts that promote deeper, explanation-based learning.

Step 3. Using high quality video as a hook, students watch and develop responses to the following questions:

- *‘As I watch this video, I found the following ideas really interested me’.*
- *‘Some questions I still have and/or things that I am still wondering about’.*

Do not ask students to summarize the video or answer low-level questions about its content. Instead, foster curiosity and question-asking that will promote long-term interest in their topic.

Stage 3: Forming Knowledge Building Communities

Step 1. Once their questions have been developed, students form into groups that comprise a Knowledge Building Community (KBC). Optimal group size should range from 4 to 6 students to maximize effective collaboration between group members. The teacher can assign groups randomly, construct pre-assigned groupings or have students self-organize into groups based on interest. The latter assignment is ideal as it ensures that each member of the group will likely have the same heightened interest in the topic under investigation.

Step 2. Using chart paper or whiteboards, each student writes down their own two or three open-ended questions they feel are most important to

Table 2. Open-ended questions generated by students in the topic of cosmology.

Understanding black holes	Understanding the universe
• How are black holes created? • Do black holes die? • Can we create black holes here on earth? • What happens inside a black hole? • Is it possible for objects to be sucked into a black hole and spit out the other side? • How does light at the inner horizon stay there? Why doesn't it disappear from the universe?	• What caused inflation? • What proof is there for the Big Bang? • If other universes exist, can we travel to them through wormholes? • Will the Big Bang ever stop? • Will life on earth be affected if the universe expands too far? • What was before the Big Bang? Is 'absolute nothing' possible?

investigate. This will result in a substantial number of questions for the KBC to consider. The teacher role here is to circulate between communities, taking interest in all questions presented. The teacher prompts students to identify whether their questions are open-ended or closed-ended and encourage them to open any questions that may be closed. Table 2 shows some examples of curiosity-based questions generated by my students after Stage 2.

Step 3. The KBC negotiates the number of questions down to two or three that they believe are most foundational to begin their work. Foundational questions should first promote the development of key concepts and basic understanding, perhaps those found in a curriculum document. For example, in table 2 the question 'How are black holes created?' would be considered foundational since it will invariably develop knowledge on stellar evolution and the associated processes that lead to black hole formation. The remaining questions should be posted in the classroom or online to remind each KBC of the curiosity-driven questions they have developed. These questions will be considered later in the KB activity as their foundational knowledge grows.

Stage 4: Building Knowledge Together

Step 1. A major outcome while working within a Knowledge Building community is the practice of collective responsibility through collaboration that focuses on idea improvement. One simple way to understand the spirit of KB is having each student practice that 'to give knowledge is to get knowledge'. By providing students access to authoritative sources, they 'get' knowledge from articles and relevant video on the Web, demonstrations and experiments, guest speakers, magazines, books and so on. Then, providing students a public online space, they 'give' knowledge back to their community so that it can be examined and improved upon by others in the community. The example outlined in this paper uses Knowledge Forum® as an online space for sharing knowledge. This software graphically represents the building of knowledge between individuals, making it easy to track the development and depth of online conversations. That being said, teachers can choose other collaborative software that works best for them to facilitate public sharing of knowledge (e.g. Lucidchart, a shared Google document, etc). Figure 1 below shows a sample of inter-connecting notes during a KB activity in one of my high school science classes surrounding the evolution of the universe. Each red circle represents a note a student has posted. The arrows connecting to each note show students building upon the notes of others in an attempt at idea improvement. Note the foundational questions prominently on display.

Figure 2 shows a small sample of idea improvement occurring as students build upon the work of others toward understanding the effects of dark energy. The series of notes show the production of new knowledge and the identification of gaps in their understanding as evident from the questions they leave behind. Working as a community, students converse on the topic and post knowledge from authoritative sources that close these gaps resulting in advances in understanding for the entire community. Note that the students begin by working at their level of competency. These competencies often grow as students refine previously posted knowledge, discover new knowledge, ask new questions and formulate new ideas to help them better understand more deeply the effects of dark energy on the evolution of the universe.

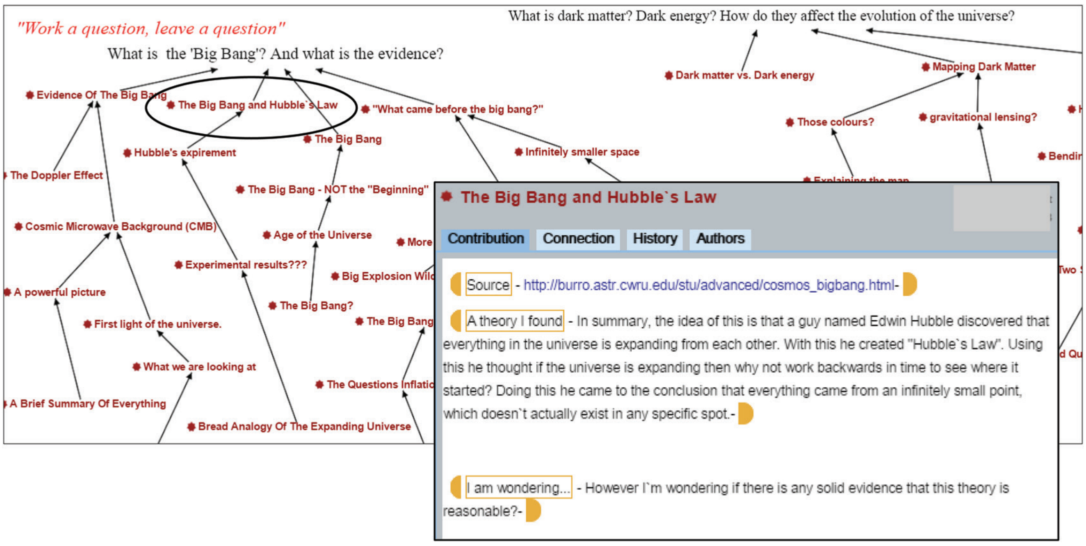

Figure 1. A sample of communication patterns surrounding the topic of cosmology and a sample note (foreground).

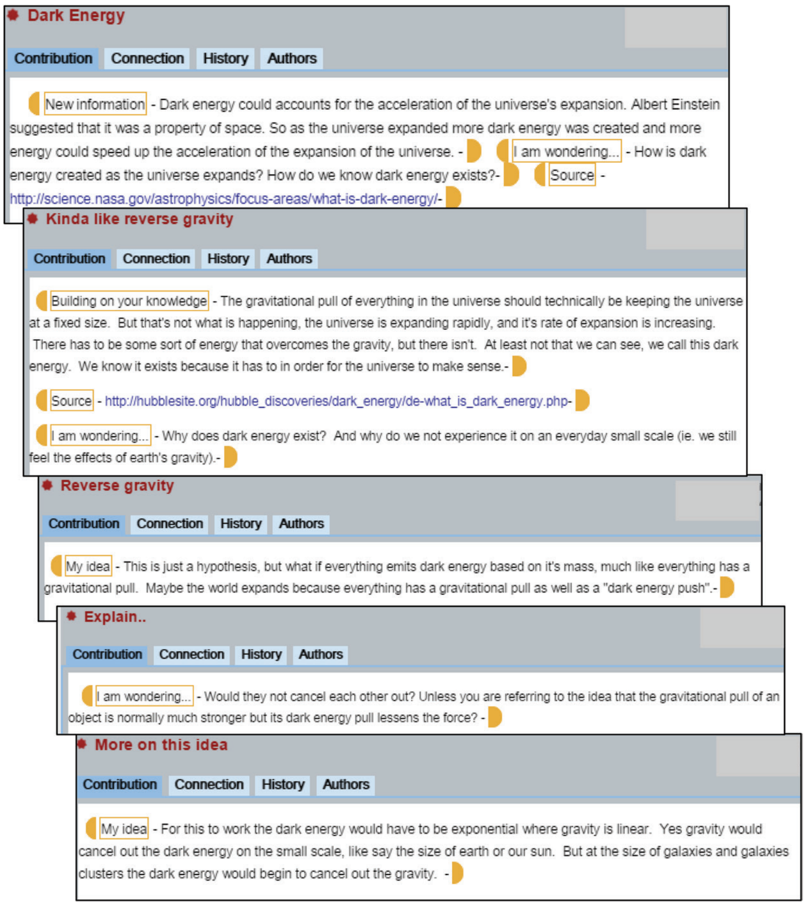

Figure 2. One section of a series of inter-connected notes demonstrating idea improvement by three students surrounding the topic of dark energy.

Table 3. A sample of the test used to measure student knowledge and understanding on cosmology.

Question No.	Question
1	The universe began with a giant explosion, like a bomb. True or False? (circle one)
3	According to modern ideas and observations, what can be said about the location of the center of our expanding universe (circle one)? (a) The Earth is at the centre (b) The Sun is at the centre (c) The Milky Way Galaxy is at the centre (d) The universe does not have a centre
14	Sketch a rotation curve (also known as the 'orbital speed' curve) for a typical spiral galaxy. Be sure to label the axes. How do the speeds of stars far from the center of the galaxy compare to the speeds of stars close to the center of the galaxy?

Step 2. Providing opportunity for students to process their community's idea improvements and knowledge development are an important component of the KB activity. After several days of KB, students meet face-to-face and discuss where their idea improvements are most and least successful and why. They also discuss where they believe they could produce better idea improvement and deeper knowledge development in their future work. The teacher provides a guiding role, such as listening in on their discussions and providing feedback, designing opportunities to complete laboratory activities, conduct demonstrations, and supply just-in-time teaching related to the on-line discussions. To aid teachers, Perimeter Institute for Theoretical Physics has produced a series of free lesson ideas, videos, laboratory activities and background information to help teachers introduce modern physics to their students [12]. Inexpensive materials and easy-to-use activities support KB by providing concrete examples that clarify abstract ideas such as expanding space, particle-wave duality and the existence of dark matter.

Stage 5: Assessing a Knowledge Building Environment

At the end of the KB activity, students meet to assess and decide upon two or three strands within their topic they believe demonstrated significant collaboration toward idea improvement and knowledge development. Students are the 'experts' in this matter as they have the most familiarity with the content developed by their community.

Once those strands are identified, the teacher can provide students several presentation choices on how to demonstrate their understanding. Group presentations to the class that ensure individual accountability are an ideal method for evaluation. This stresses the importance that when working as a group they will be evaluated as a group. Alternatively, students can create individual portfolio summaries of one or more of the strands, highlighting not only content knowledge but also detailing how idea improvement developed through collaboration. Similar to a literature review, the portfolio should directly reference the work of other members of the group that highlights the collaborative nature of idea improvement in their work.

Learning outcomes and Knowledge Building

How well do students learn in a KB environment when they collaboratively define problems to study then take control of the questioning, goal setting, and assessment that is normally under control of the teacher? To determine this, a series of nineteen questions on the Big Bang, the expansion of the universe, dark matter and dark energy were administered to the KB community at the end of the activity referred to in figure 1. These questions were a series of multiple-choice, true/false, and short essay designed by university researchers to measure knowledge and understanding in their first year university-level introductory cosmology course [13, 14]. This course was primarily teacher-centred, meaning that the teacher was in control of the content, how it was delivered, and how students interacted with that content. The question results from this course were then compared to the answers produced by the KB community. A sample of the test questions is shown in table 3.

Figure 3 shows a comparison between the two groups for the multiple choice and true/false responses. Figure 4 shows the comparison between

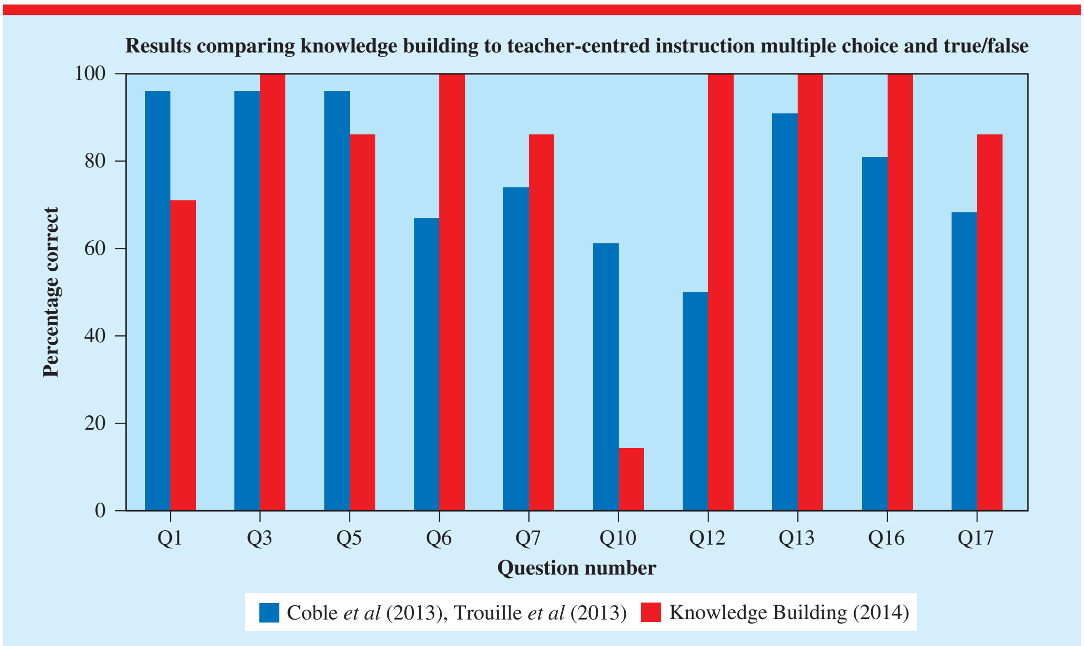

Figure 3. Multiple choice and true/false results comparing Knowledge Building to a teacher-centred approach to learning.

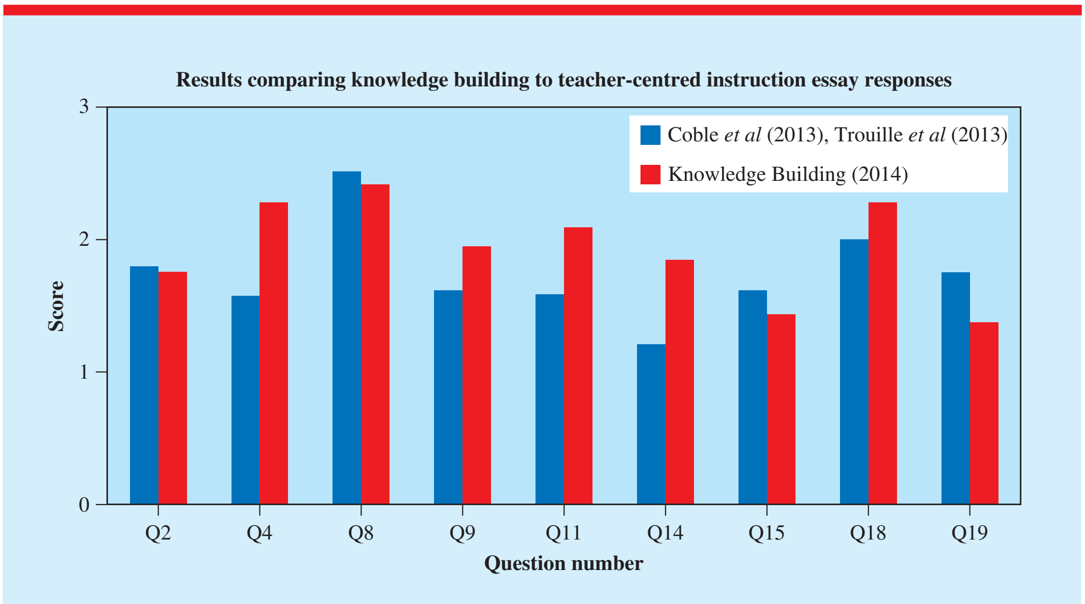

Figure 4. Essay response results comparing Knowledge Building to a teacher-centred approach to learning.

the two groups surrounding the essay response questions. Qualitatively, we see the two groups closely match in their responses indicating similar outcomes in terms of knowledge and understanding. A subsequent statistical analysis conducted upon the data produced by the two groups found no significant differences on the outcomes of nearly all of the nineteen questions. These findings suggest that students working in these two widely different learning environments—teacher-centred and

KB—produced similar learning gains surrounding concepts in cosmology. The results presented here and elsewhere [15, 16] should ease teacher concern that students might not learn the 'right' content or may lack self-motivation to learn when working collaboratively largely absent of teacher control.

Conclusion

Knowledge Building mirrors how the scientific world works beyond the classroom—collaboratively building and improving upon the knowledge and ideas of others. When applied to the classroom, KB can provide students with a unique opportunity to engage with cutting-edge modern physics content at their level of competency that would otherwise receive little consideration. By taking charge of their learning through curiosity-based question asking, students assume the planning, goal setting, content expertise and assessment toward answering their questions. This frees the teacher to act as a mentor/coach without the need for deep content expertise. Courses of study that require independent study on behalf of the student are ideally suited to a collaborative, Knowledge Building approach to learning.

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References

[1] Zeilinger A 2003 Quantum teleportation *Sci. Am.* **13** 34–43
[2] Riess A G and Livio M 2016 The puzzle of dark energy *Sci. Am.* **314** 38–43
[3] Miller M C 2016 Gravitational waves: dawn of a new astronomy *Nature* **531** 40–2
[4] Scardamalia M and Bereiter C 2003 Knowledge building environments: extending the limits of the possible in education and knowledge work *Encyclopedia of Distributed Learning* (Thousand Oaks, CA: Sage)
[5] Gallagher S A, Stepien W J, Sher B T and Workman D 1995 Implementing problem-based learning in science classrooms *Sch. Sci. Math.* **95** 136
[6] Blumenfeld P C, Soloway E, Marx R W, Krajcik J S, Guzdial M and Palincsar A 1991 Motivating project-based learning: sustaining the doing, supporting the learning *Educ. Psychol.* **26** 369–98
[7] Sharan Y, Sharan S 1990 Group investigation expands cooperative learning *Educ. Leadership* **47** 17–21
[8] Scardamalia M 2002 Collective cognitive responsibility for the advancement of knowledge *Liberal Education in a Knowledge Society* vol 97 (Chicago: Open Court) pp 67–98
[9] Hunter R 2004 *Madeline Hunter's Mastery Teaching: Increasing Instructional Effectiveness in Elementary and Secondary Schools* (Thousand Oaks, CA: Corwin Press)
[10] Berger W 2014 *A More Beautiful Question: the Power of Inquiry to Spark Breakthrough Ideas* (London: Bloomsbury)
[11] Rothstein D and Santana L 2011 *Make Just One Change: Teach Students to Ask Their Own Questions* (Cambridge, MA: Harvard Education Press)
[12] https://store.perimeterinstitute.ca/
[13] Coble K *et al* 2013 Investigating student ideas about cosmology II: composition of the universe *Astron. Educ. Rev.* **12**
[14] Trouille L E *et al* 2013 Investigating student ideas about cosmology III: big bang theory, expansion, age, and history of the universe *Astron. Educ. Rev.* **12**
[15] Zhang J, Scardamalia M, Lamon M, Messina R and Reeve R 2007 Socio-cognitive dynamics of knowledge building in the work of 9-and 10-year-olds *Educ. Technol. Res. Dev.* **55** 117–45
[16] van Aalst J and Chan C K 2007 Student-directed assessment of knowledge building using electronic portfolios *J. Learn. Sci.* **16** 175–220

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