Learning about Scientific Inquiry Through Engineering

Jessica Harwood, Al Rudnitsky

Smith College

The broad question addressed by this study is "how should ideas from engineering be integrated into the school curriculum?" Efforts to include engineering in the K - 12 curriculum have increased considerably in recent years. Many of engineering's educational advocates hold the position that engineering should not be a "stand-alone" school subject or, at the very least, not be exclusively so. This paper is a case study of integrating engineering into the existing curriculum. The more focused questions addressed here include "what does engineering bring to teaching and learning when it is integrated with other subject matter?" and "what are some important things to consider when attempting this sort of integration?" The evidence needed to answer these questions is ultimately to be found in student learning outcomes. This, however, is not the only source of evidence. How the integration of engineering into other content areas affects teacher thinking and behavior also speaks to these questions. The planning and teaching of a novice teacher, as told in her own words, is the focus of this paper. The teacher is working in the subject area of science, more specifically she is teaching ideas about scientific reasoning to middle school students. The instructional approach she follows relies on ideas from engineering and engineering education. Should these ideas prove useful to a beginning teacher who is working with a very complex and important subject matter, it would lend considerable support for this sort of curricular integration.

Theoretical framework

“Reasoning scientifically” or “thinking like a scientist” are two expressions frequently used by educators to describe an important, long held and almost universally shared educational goal; see Dewey [1]. Recent suggestions for reform in science education such as those from AAAS [2], or NRC [3], reflect this by making scientific inquiry a primary learning goal and also recommending that the actual conduct of scientific inquiry serve as a core instructional strategy. “Reasoning scientifically” and “thinking like a scientist” are expressions so widely used they have achieved the status of slogans. The danger with slogans is that we sometimes stop thinking about their meaning. Such would be unfortunate because these expressions convey the essence of a learning goal that is of the utmost importance if students are to be well educated and prepared to participate in what Bereiter [4] refers to as the knowledge age. The reasoning and thinking alluded to by these expressions, and what we mean when we use the term “scientific inquiry,” go beyond science and encompass learning outcomes such as understanding what it means to “know” something, understanding where knowledge comes from, being able to evaluate the believability of a knowledge claim, and understanding why knowledge is always improvable – never final.

Despite the importance of scientific thinking, it continues to be an elusive educational goal. Many students, even advanced students, do not grasp how scientific theories arise and the manner in which evidence is used to support or call those theories into question. Experts such as Barr [5], Scharmann [6], and Kracjik [7] and most assessments agree that students tend to view science as a collection of facts and typically do not understand the process of knowledge building in science. There are many reasons for our lack of success in teaching about scientific inquiry. One significant reason is that there is considerable variation among educator's conceptions of inquiry. This is evident in the way inquiry is typically taught. In most classrooms inquiry consists of "teaching" the steps of the scientific method. Thus students come to see inquiry as a procedure, a sort of recipe that scientists follow to make discoveries. This is a very limited conception.

One's conception of inquiry is part and parcel of a broader conception of knowledge and knowing in general. Inquiry, rather than a procedure, is a way to look at and think about one's world and what counts as knowledge. Issues surrounding knowing and knowledge have generated increasingly widespread interest among psychologists and philosophers who term these understandings "personal epistemology." Hofer [8] describes personal epistemology as one's beliefs about knowledge, about knowing, and about oneself as a knower. These beliefs encompass notions such as the certainty of knowledge, structure of knowledge, sources of knowledge, and justification for knowing. Hofer [8] provides the following illustration of epistemic questions: "As you learn about a topic "how will you evaluate and assess the veracity of what you read and hear? Whose authority will you accept – and why? What evidence will you decide is acceptable justification for particular recommended choices of action? How certain are you that what you read is true, that it is supportable, that it can be believed? How will you reconcile your own experience with those of experts? When do you decide that you know enough and your understanding is adequate? These … concerns represent an illustrative sample of questions whose answers will be influenced by one's personal theory of knowledge and knowing, or what has been called personal epistemology." (p. 43)

Clearly these ideas are complex and apply to many subject area disciplines in addition to the sciences. Helping students develop these understandings will require instruction that extends over many grade levels, crosses disciplinary boundaries, and puts learners into contexts where they "need" to engage in these kinds of thinking. Accomplishing this will challenge teachers and students. The study reported here is more about teaching and teachers than it is about learning and students. The question and need addressed in this study is how can we best scaffold and frame the work of teachers as they attempt to teach about scientific inquiry and "how do we know what we know." Neither teaching the "scientific method" nor the traditional laboratory experiment nor trying to embed inquiry into the teaching of "regular" science content have proven to be very successful or effective instructional approaches. The work reported here investigates whether engineering might provide a context that would help teachers think about and plan for fruitful approaches aimed at teaching about inquiry and scientific reasoning. The study attempts to bridge disciplinary boundaries and create a learning environment where middle school students need to engage in scientific thinking. The study bridges boundaries by drawing on engineering and engineering education as well as more "mainstream" science as sources of ideas for instruction and to broaden our view of "what it means to know something."

Does engineering hold out the promise that it might provide valuable ideas and insight about teaching scientific reasoning? We believe it does. First, the kind of thinking and problem solving characteristic of engineers is supported by ideas about knowledge and knowing – ideas that are quite in keeping with those of scientific reasoning. The personal epistemology focusing on how we know things, the strength of knowledge claims, and how they are related to evidence is as crucial for the field of engineering as it is for the sciences more generally. Engineers are constantly making judgments about design, material, and underlying theory as they engage in problem solving. Because engineers recognize that solutions to problems are only as good as the knowledge that supports them, and that sometimes solutions must be offered with incomplete knowledge, they view making constant knowledge improvement central to their work. The engineering problem solving process or, better yet, inquiry process, is often designated "engineering design" and consists of the following steps [9]:

1. Identify the need or problem.
2. Research the need of problem
3. Develop possible solutions
4. Select the best possible solution
5. Construct a prototype
6. Test and evaluate the solution
7. Communicate the solution
8. Redesign

As was the case with the scientific method, describing engineering design in terms of steps increases the risk that educational treatment will focus on the steps and miss the broader understanding about knowledge and knowing that turn these steps into a way of thinking. Asking the right questions and answering them in the best, most believable and coherent manner is at the heart of the process. Constructing prototypes in order to make decisions bears a close family resemblance to experimentation aimed at answering questions. Clearly the goals of both science and engineering education are served if students develop these understandings.

Etheredge and Rudnitsky [10] examine instructional practices employed in teaching inquiry and find theoretical support for several characteristics that should form the basis for designing effective instructional environments for teaching about inquiry. These characteristics include:

- Collaboration and its accompanying social discourse
- Authenticity in that rather than schoolwork for schoolwork's sake, students need and want to know about something
- Explicitness and reflectiveness focused on knowing, knowledge, and how these are related to evidence and procedures for gathering and interpreting evidence

Among the challenges for teachers is to find or construct a context for actually pursuing the creation and improvement of knowledge in this authentic manner. Engineering education often engages students in "hands-on" problem solving. Much of this problem solving could be characterized as authentic and also lends itself to collaboration. In a sense, students of engineering are often working in microwolds that provide context and control of some system of variables. Engineering education, as well as benefiting from effective instruction aimed at epistemological beliefs, could be a source for both effective problem contexts supporting student inquiry and for a conceptual framework that helps teachers think about instruction.

Etheredge & Rudnitsky have developed a set of guidelines for designing inquiry units. Students asking authentic questions and trying to answer them is the foundation of learner engagement in an inquiry unit. Key aspects of an inquiry unit include:

- Students are immersed in a "system" of variables that together create a microworld for student investigation and problem solving. It is essential that this microworld be both engaging and (at least largely) under learner control.
- Students are made aware of the problem or problems they will have to solve at the unit's conclusion. Using a concept developed by Brown and Campione [11], we refer to these as consequential tasks. In this way, students can think about the knowledge of the system they will need to support problem solving.
- Most of the student work involves asking questions that get at the needed knowledge and devising ways to answer those questions.
- There are multiple levels of discourse and collaboration.
- Teacher must recognize the need and readiness for students to move to a higher level of understanding and take advantage often by teaching a benchmark lesson.
- Students get to assess the level of their knowledge by tackling the consequential task(s).

This study describes a unit devised following the guidelines suggested above. Engineering serves as the source and inspiration for the context and thinking about the design of this instructional environment. That is to say, a major contribution of engineering is in how the teacher thinks about the unit. This study seeks to explore whether this engineering context facilitates a novice teacher's thinking as she plans and implements an inquiry unit. The study also explores the ways in which the cyclical nature of the engineering design process can contribute to middle school student's understanding of how we come to know things and how and why we constantly need to improve our knowledge. The instructional environment engages students with problems of designing procedures for gathering evidence, analyzing the results of those procedures, modifying and improving their procedures, and communicating their conjectures and conclusions. If ideas from engineering and thinking with an engineering framework helps a novice teacher negotiating the complex instructional territory of an inquiry unit, it would provide support to the notion that engineering brings something of considerable value to this enterprise. What follows is the self-report of a graduate student in a teacher education program as she plans and implements an inquiry science unit. Conclusions are written from the perspective of a teacher educator.

Teaching scientific inquiry: A description of the unit

During the year 2004, I planned, revised, and twice taught a unit exploring a straw projectile launcher system. The launcher propels a drinking straw through air pressure generated when a weighted rod is dropped inside of a tube. The system has great manageability in the context of a middle school classroom and with middle school-aged students and yet also has many variables that can be manipulated, including the force of the weight stick (as regulated by the height it is lifted), the angle of the launch, the amount of contact between the straw and the launcher, as well as variables related to the straw, its weight, length, and tip. The purpose of the unit was for students to develop a more sophisticated understanding of scientific inquiry by inquiring about the launcher system through questions and experiments in order to understand it better. Through experimentation, the students developed comprehensive data and graphs that in the end would allow them to solve the consequential task of hitting a target (the location of which students did not know until they actually encountered the problem) with the straw. Through the process, the students developed the abilities to come up with testable hypotheses, test a hypothesis with repeated trials, make conclusions and inferences from data, present data visually and orally, and share information in a community of scientists. Throughout these units my actions as a teacher were guided by my conception of what scientific inquiry is all about and what activities help learners understand scientific inquiry. Engineering provided one of the "lenses" I used to think about what I was doing.

The first unit took place at the Smith-Northampton Summer School. The school meets for five weeks and students enroll in three courses/classes. The "engineering" class was composed of fifteen students, ranging in grade level from fifth to ninth. The students had varying ranges of interest, commitment, achievement, and understanding of science. Three of the students were taking the class because they had failed science and the other twelve were there for enrichment. This straw launcher unit lasted the entire five weeks and each lesson was two hours long.

The second unit took place during the first four weeks of school for a sixth grade class at the Smith College Campus School, a independent school that serves as the Smith College laboratory school. Because of time constraints, there were only two lessons per week and each lasted an hour. There were twenty-one students in the class, many of who are exceptionally high achieving. The students have been introduced to the idea of inquiry to understand a system during each grade in the school and sixth grade represents the culmination of these units. The differences in these two contexts and time frames made the two iterations of the unit quite different.

The lessons generally began with the entire group meeting together in order to share ideas and for me to help the students to frame the task of the day. The majority of class time was spent in groups of three that were very deliberately picked in order to balance ability levels, behavior, and learning styles. Except for the communal conversations and sharing, each group worked on the inquiry independently. The goal with the groups was to simulate research teams and for the class to operate like a community of scientists sharing their findings.

Both units began with a day of exploration to allow the students to become engaged in the system and understand its various aspects. The opening of the unit was framed with the question, "What is the best launch?" This question is purposely ambiguous to allow the students to define what best is and to try out several different variables in pursuit of the "best" launch. This enabled the students to discover what the system was capable of and decide for themselves what a "best" launch might be, whether it was height, distance, or accuracy. Across the board this lesson served to spark an interest and enthusiasm for the system and the exploration of it. The students had begun to think about the different ways to manipulate the system. In trying to achieve the "best" of whatever they had established as the rubric for their experiment, the students necessarily had to experiment with many of the different variables inherent in the system. They realized that they could adjust the angle of the launch, the amount of pressure applied (that was in turn transferred to air pressure to propel the straw), the amount of contact between the straw and the tube from which it was launched, and aspects of the straw, such as length, tip, and other attachments, like fins. However, for the purposes of this first experience with the system and also to keep the work from getting far more complex than I was ready to support, I stipulated that straw length and treatment of the tip would remain constant.

These experiments provided the data for a discussion about the important aspects of the system. Following this first lesson, I wanted to ensure that all of the students were on the same page in terms of understanding the system. During the fall, I had the students respond to the experience for homework by drawing and labeling the system, making a prediction about the system based on what they had done and speculate on how best to learn about the system now. During the summer, the longer classes permitted us to have a fruitful discussion immediately following their initial experiments (for the record, I would have all groups complete this assignment – with or without lots of instructional time). For the discussion with both classes, we discussed the notion of "best" with regard to this system. We then described the system in terms of all the variables they encountered in their initial work. This enabled us to create a common language with which to discuss the system and to label the parts of the system. We named the parts of the system together (e.g. the plunger for the weight rod or the spaghetti-o for the o-ring on the launcher). I told the class during the unit that they would need to know the system well enough to be able to hit a target with a straw no matter where the target was within the range of the launcher's capacity. I demonstrated what I meant by this. This was the "consequential task" and served as a goal throughout the unit, one that always helped focus the student's investigations and attention back to the questions of import.

Once the students had a list of the variables and an understanding of what a variable is, each research group developed a hypothesis about how a particular variable will affect the system. After developing the hypothesis, research groups created plans to test it. The subsequent work was "all over the map" in terms of what and how students were working. I needed to provide more structure and guidance and so I limited the variables with which the class initially worked and asked all the research groups to try to figure out how they might be able to determine the relationship between the angle of the launch and the distance the straw flies. We had a discussion that provided an opportunity to critique their previous experiments. I hoped that they would come up with the need for holding certain variables constant, testing methodically, and doing repeat trials. Sharing their ideas as a whole class, raising questions, and discussing findings helped establish a more organized and rigorous system of experimentation. This phase of the instruction served as a way to lead the students to think about the design of experiments and what they need for a testable experiment.

We spent the next few lessons testing the impact of different variables on the launch. We began with the angle of the launch: the group's initial task was to establish a hypothesis for how the angle would affect distance. From the hypothesis and the results of their initial trials, the students discussed and made decisions about issues crucial to scientific reasoning and the believability of knowledge, e.g., what data points to test and how many trials to do at each data point. Students created forms to record their data in more organized ways. These forms included not only the aspects of the system that students varied but also values they held constant. To add consistency and facilitate discussions among groups I thought it would be helpful if all the research groups used the same data sheet. I created a table that consolidated most of the ideas that students were already including. The groups that were not as far along were quite ready for the support this structure provided and it helped them become more systematic in the design of their experiments. Once the groups had either tried all of the data points that they intended or the time had run out, the students had to re-assess their hypothesis and also figure out a way to represent it for the rest of the class. In the Campus School class, the students were working on graphing in their math class so this was a good opportunity to challenge them to graph their launcher data. The groups in the summer school class had carte blanche as far as how to communicate their data and some groups chose to graph it while others did not. In either case, each group had the opportunity to present their findings. During the summer school class we had the time for each of the groups to demonstrate that they could hit a target by varying just the component of the system that they had been testing as a variable.

In order to support the kind of discourse one would find in a scientific community, it seemed important to have at least some groups working on the same questions. In this way, conflicting results, new methods, and other issues would provide appropriate and focused topics of conversation. I organized the work so that half the class would be testing one variable and the other half another. One day was devoted to the plunger height and the o-ring height while another concerned the actual projectile, varying the tip mass and the straw length. By splitting the research teams into two problem groups, each group was more accountable for their research so that their presentations held more weight. For these experiments in the summer the groups were required to switch data with each other so that a group that had not yet experimented with the variable could use the data to hit a target. At the Campus School, the students simply presented their findings to each other with graphs that represented their data.

The units concluded in different ways because of the difference in available time. During the summer school program, we had had the opportunity to solve a problem structured like the consequential task each day with each variable. I wanted to provide the students with a challenge that would be more exciting and thought provoking for the final consequential task so they had four stations of consequential tasks. I viewed this as an opportunity for the learners to be engaged in prototyping. One station required the students to another hit a target smaller than they had been practicing on twice, varying at least two variable in the system; the next was the longest possible launch, taking into account all of the variables; another was to hit a height target on the wall, making an inference from the length data that they had gathered; and lastly, the students had to try to project the straw under a table, trying to make it go as far as possible without hitting the table. During the very last day, I allowed the students to design their own experiments with the system because they had developed many curiosities over the course of the unit. Many students designed their own projectiles with fins of all different shapes and sizes; two groups tried to test the precision of the system; and one student worked on trying to apply a formula to predicting the length of the launch.

At the Campus School on the second to last day, I mixed the students up into groups of four with students from different research groups. The goal that the students had was to look at their data and graphs and write down a hypothesis for each of the variables to help them with their consequential task. This activity was very important and also needs more time, emphasis, and scaffolding. On the last day, the original groups were challenged to three stations of consequential tasks: the shortest launch, the longest launch, and the most accurate. For accuracy, they had to try to hit a target with as much specificity as they could achieve.

Reflections about the unit.

This was the first time that I taught scientific reasoning. I learned a great deal about scientific reasoning and how to teach it by teaching the two units. In both units the students benefited from the opportunity to explore a system and develop scientific methodology on their own allowed students to grow in their ability to reason scientifically and think about the importance of evidence when it comes to knowing something.

A major realization and a qualifier for what follows is realizing the importance of having time for students to pursue the investigation. This is not the kind of teaching and learning that can be hurried as became clear from the Campus School experience. It was important to have two-hour blocks during the summer to allow for substantial experimentation and discussion. One hour was not even enough time for the students to experiment with all of their data points. In fact, when the Campus School students evaluated the experience at the end, they thought that in order to know the system better they would try more data points and do more trials – essentially spend considerably more time with the system. Overall, the unit necessitates more than the eight hours that we devoted to it this fall. It was a great advantage to have the time for the students to experiment with whatever interested them from the system, after cultivating the methodology for experimenting and knowing the system well enough to know what sorts of questions to ask during the summer.

Beginning with the question of the "best" launch was a good way to begin the exploration of the different possibilities of the system. It certainly allowed the students to delve into the system with enthusiasm, but for many students, the nuances of "best" were not immediately clear. Many students assumed that best was the distance of the launch. In the summer school class, best uniformly meant farthest launch and many of the students in the class became fixated upon this goal. The challenge became diverting their attentions from the fixation of the best possible launch, particularly with the summer school students who had begun to compete with each other. In fact, it was only the Campus School students, who had already had exposure to inquiry units, who thought that it could be accuracy or height too. Providing more guidance than asking for the best launch is a good idea with groups who have little experience with inquiry. Despite some narrow interpretations of "best," all students became aware of the different components of the system and the basics of how it works. Because the students were discovering the system initially alone they were excited about their findings and therefore the system. They were proud of their own discoveries and they embraced the ambiguities in finding the "best" system.

From there, it would have been ideal to let the students discover for themselves how to find out and test relationships between variables. During the summer, we were able to have a fruitful discussion about this and the students had enough leeway to develop their experiments on their own. Giving them a data sheet after a few days was very helpful to the students for structuring their experiments and helping students become aware of the need to hold some variables constant, try many different data points, and do repeated trials. Perhaps the students would have gained more from developing their own data sheet, but for the purposes of this unit, it was very helpful and also helped to deal with time constraints (even in the summer version of the unit). During the fall, we did not have enough time to discuss and debate the different variables and their relationships both in small groups and the whole class.

A challenge in teaching the unit was finding a way to scaffold the students' learning so that they would realize how best to go about the experiments on their own. During the summer, the students had some great realizations about what data points they would need, how to represent the data, and how variables the system was. One day, when groups were sharing data with the whole group one of the younger students spontaneously graphed his group's results on the board, which led to other groups graphing their data too. This same student also began to attempt an explanation of the physics of the system, which sparked a lively discussion among many of the students in the class. It turned out that the system was quite delicate and students had begun to question the precision of the launchers. Many speculated that they did not all perform comparably. One group had begun to implement a rudimentary error analysis, which provided an excellent opportunity to discuss this issue and to derive a simple t test with the group. However, with the limited time during the fall, it was harder to lead the students to the realizations about experimental design. Some of the ideas we gave to them along with the notion of the scientific method and following strict, pre-set steps for the experiment. Because they had less of a chance to experiment with the system and establish their own methodology, they seemed less engaged in the whole process. Likewise, they had less of a chance to discuss and explore their ideas and findings with each other and therefore did not progress in their own thinking too much.

The greatest success of the unit during the fall was the day when the students finally got the chance to really explore and assess the system on their own when they were trying to establish hypotheses for each variable. The groups became quite interested in the data, outliers, and trends. Three groups were particularly concerned with inconsistent data and designed their own experiments to help to explain previous results or to re-do the incomplete experiments with data points that they had decided were necessary. The enthusiasm and commitment of the students on this day was markedly higher. The greatest advantages of such an inquiry unit are the independent realizations and experimentations coupled with discussions that allow the students to teach each other and explore together.

Another wonderful advantage of this unit is the group work. It provided opportunities for students to work collaboratively, teach each other, excel in many different disciplines, build community, and learn a respect not only for the scientific process but also for the thinking of others. For both units, I was very deliberate in choosing the groups. I tried to mix students of different ages and interests in the unit. For the most part, the groups became invested in the project together and were proud of the work that they had done. Different students were able to shine in different areas. It was sometimes difficult to foster whole-class collaboration because the student research groups became so possessive of their findings. Perhaps this is not unlike the real world of science. It is something that I'll make a topic of discussion in the future.

Conclusions

This case study, while exploratory, provides support for using ideas from engineering to teach students about scientific inquiry. It is clear from student performance on the consequential problems, that is, their impressive ability to hit a target of hitherto unknown location with a straw, that they learned quite a bit about the system and did so through their own efforts. Whether or not they constructed ideas about evidence, scientific reasoning, and how we know what we know in ways that will transfer to other contexts is something we don't know. Students clearly learned about the conduct of scientific inquiry and this provides impetus to examine transfer of learning.

More central to this case study is the evidence provided by the teacher. This is a novice teacher who has taught, twice, a very impressive and high quality inquiry unit. The straw launcher units had a sophistication and focus on what really matters. Having worked with many veteran teachers attempting to teach about inquiry, I can fairly say that this unit was remarkable. The teacher's comfort level with the unit is impressive. While there are many ways to improve the teaching of this unit – many that the teacher herself brings to light, which is in itself a noteworthy accomplishment – the way this teacher was able to think about what students were doing, make adjustments as the unit proceeded, scaffold student thinking and activity at appropriate times was impressive. At many times in her description and reflection on the units she uses ideas from engineering. While she doesn't identify them as such, activities such as having to solve a practical problem, the need to communicate your ideas clearly, and prototyping are emanate from engineering.

As noted, many teachers with considerably more experience have enormous difficulty thinking about scientific reasoning and inquiry, let alone teaching it. Here a beginning teacher was able to maintain a vision about what was important in the unit and make the sorts of teacher decisions needed to support this vision. Was engineering responsible for this? Well, the teacher herself deserves much of the credit. The guidelines provided by Etheredge and Rudnitsky [10] were also helpful. Nevertheless, the complexities and challenges to a teacher, especially a beginning teacher, are formidable. Engineering and engineering education provided the source ideas that helped shape the context of a manipulable system, having to solve a problem that required considerable knowledge of the system, and having students working as a team and communicating ideas about it all supported the work of this teacher. I believe that the engineering "nature" of the experience provided a frame of reference that allowed the teacher to think about the instruction and student learning. We believe that there is considerable work to do. We also believe that engineering can provide ideas and contexts that support teachers and teaching in a variety of subject areas.

Author's Note

The final version of this paper will include photographs of the apparatus. The poster presentation will have many photographs and examples of student work during the units.

Bibliography

1. Dewey, J. (1910) *How we think*. Boston: Heath

2. American Association for the Advancement of Science (AAAS) (1993) *Benchmarks for scientific literacy*. New york: Oxford University Press.

   American Association for the Advancement of Science (AAAS) (1989) *Project 2061: Science for all Americans.*

   American Association for the Advancement of Science (AAAS) (2001) *Atlas of science literacy*. Washington, DC: AAAS.

3. National Research Council (NRC) (1995) *National science education standards*. Washington, DC: National Academy Press.

4. Bereiter, C. (2002) Education and mind in the knowledge age. Mahwah, N.J. : L. Erlbaum Associates

5. Barr, B. B. (1994) Research on problem solving: Elementary school. In D. L. Gabel (ed.) *Handbook of research on science teaching and learning*. New York: Macmillan.

6. Scharmann, L. (1992) Teaching evolution: The influence of peer instructional modeling. Paper presented at the annual meeting of the National Association for Research in Science Teaching. Boston, MA.

7. Krajcik, J., Blumenfeld, P.C., Marx, R.W., Bass, K.M., Fredricks, J. & Soloway, E. (1998) Inquiry in project-based science classrooms: Initial attempts by middle school students. *Journal of the Learning Sciences*, 7 (3/4), 313 – 350.

8. Hofer, B. K. (2004) Epistemological understanding as a metacognitive process: Thinking aloud during online searching. *Educational Psychologist*, Vol. 39, No. 1, 43 – 55.

9. Science and Technology/Engineering Curriculum Framework (2001), Malden, MA: Massachusetts Department of Education

10. Etheredge, S. & Rudnitsky, A. (2003) *Introducing students to scientific inquiry: How do we know what we know*? Boston: Allyn & Bacon.

11. Brown, A. & Campione, J. (1996) Psychological theory and the design of innovative learning environments: On procedures, principles, and systems. In L. Shauble & R. Glaser (eds.) *Innovations in learning: New environments for education*. Mahwah, NJ: Lawrence Erlbaum Assoc.

AL RUDNITSKY, Drexel University, B.A. 1970; University of Massachusetts, M. Ed. 1971; Cornell University, Ph. D. 1976; is a professor of Education & Child Study at Smith College.

JESSICA HARWOOD, Brown University, B.A. 2002; is a graduate student in Education & Child Study at Smith College.