Teaching Critical Thinking Skills and the Nature of Science through Problem-based Learning

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This is a qualitative study of a subset of three problem-based units taught in high school (ages 15-18) and middle school (ages 11-14) in the USA. The process of problem-solving as described by Swartz and Parks were used to create authentic science units in which critical and creative thinking skills were directly taught. Instead of teachers telling the students about the Nature of Science or asking to read about it, students reflected on the process using the critical thinking skills they had learned. Based on results from classroom observations and teacher and student interviews, by situating science instruction within the context of the process of critical thinking and in addition to reflection on those skills, process and content learning were enhanced. This led to a broadening of the appreciation of students of the Nature of Science and an overall richer understanding of how science works. Keywords: problem-solving, science, problem-based teaching units, critical thinking skills, nature of science

1. Introduction

The National Science Education Standards (National Research Council, 1996) defines inquiry as “…the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work” (p 23). An appropriate understanding of the nature of science (NOS) has been linked to the development of scientific literacy (DeBoer, 1991). Previous research has shown that teachers’ views of NOS are not consistent with contemporary conceptions of the scientific endeavor (Abd-El-Khalick & Lederman, 2000; Gallagher, 1991; King, 1991; Lederman, 1992). Some important aspects of NOS have been advanced in recent reform documents including Science for All Americans (American Association for the Advancement of Science, 1993) and National Science Education Standards (NRC, 1996). These aspects include that (a) scientific knowledge is both reliable and tentative, (b) no single scientific method exists, but there are shared characteristics of scientific approaches to science (e.g., scientific explanations are supported by, and testable against, empirical observations of the natural world), (c) creativity plays a role in the development of scientific knowledge, (d) there is a crucial distinction between observations and inferences, (e) though science strives for objectivity, there is always an element of subjectivity (theory-ladeness) in the development of scientific knowledge, and (f) social and cultural contexts play a role in the development of scientific knowledge.

National reform documents in the United States such as National Science Education Standards and Benchmarks for Science Literacy (AAAS, 1993) recommend that teachers help K-12 students to not only acquire understandings of scientific knowledge and develop skills needed to conduct scientific inquiries, but also to achieve an understanding of nature of science (NOS). Various approaches have been undertaken to enhance teachers’ views of several important aspects of NOS with differing levels of success (Abd-El-Khalick & Lederman, 2000). The current study describes case studies of teachers and students involved in infusing critical thinking skills into problem-based learning as they participate in scientific inquiry and nature of science activities.
2. Problem-based Learning in Science

The process of scientific thinking are fundamentally those of problem solving imbued with the standards of judgment required for empirical evidence before ideas and claims being considered are worthy of acceptance by the scientific community (Swartz, 1997). The problem-solving process as described by Swartz & Parks (1994) first considers what is the problem and what facts are needed to define the problem, secondly, what are the options and possible solutions, thirdly which options or solutions are best, what might the consequences of each option be and the value of those consequences, and finally describing how to solve the problem. For example when solving a problem in science, diagnosing the cause of the problem involves judging the reasonableness on the basis of observable evidence only when the variables have been identified that provide the competing causal possibilities. In addition predictions about future outcomes are based on supporting data and past patterns of events. Problems in science often require a variety of information from a variety of sources. Judging how reliable the information might be is an important part of scientific thinking. In fact, without learning the process of science, students will not be able to engage fully in scientific thought. In this approach, teachers used the direct instruction of critical and creative thinking infused into content to solve scientific problems. Five specific types of thinking were incorporated which includes problem solving and the component processes of causal explanation, prediction, comparing and contrasting, and determining the reliability and accuracy of sources of information.

The teachers in this study realized that solving complex problems requires critical and creative thinking skills that are as important for students to learn as the content. Guided by teachers, the students developed an overall question(s) with focus questions and were then provided opportunities to apply the thinking strategies to guide them through the aspects of the science they were learning as they answered the problem questions. Students learned each thinking skill in the process by using the strategies described in the Swartz & Parks (1994) book. The units began with an overall introduction to problem solving followed by reliable information as one of the first sub component skills covered, then causal explanation, prediction, and comparing and contrasting were taught as the problem-solving unit proceeded. The advantage of using this conceptual framework (Swartz & Parks, 1994, p. 8) in the form of problem-based units in science is that the critical thinking skills are purposefully used repeatedly by the students in different contexts throughout the unit and can be revisited as often as needed. In addition, as suggested for the learning of NOS (Akerson, Abd-El-Khalick, & Lederman, 2000), there was an emphasis on students’ metacognitive reflection regarding the way they solved the problems to guide and improve their process skills. Instead of teachers telling the students about NOS or asking to read about it, they experienced the NOS and reflected on the process using the critical thinking skills they learned.

3. Case Studies

A subset of three problem-based units in high school (ages 15-18) and middle school (ages 11-14) are represented in this study. Though different in content and complexity, the structure of the units was similar. Whitaker’s high school students began their unit by investigating their school grounds and examining aerial photographs of the area. Based on their observations, they determined where they would locate 10m² study plots on their school campus (Hagevik, 1999). Their overall problem question was “What is the relationship between the living and non-living components of the environment”? Students generated 15
to 20 questions they thought would help answer the overall question. Some of these included, “What is the relationship between the light and dark areas, moist and dry areas, areas of grass and trees, air temperature to soil temperature”? These questions were then categorized into abiotic, trees, animals, and vegetation cover. Similarly in Owens’s middle school classroom where they were studying a unit on rocks, minerals, heat, and sound, students brainstormed questions such as, “Can the cave be disguised? How can we keep warm? What are the rocks like? How can we use light to survive?” They categorized their questions into heat in the cave, light in the cave, transmitting sound in the cave, and characteristics of raw materials in the cave. Similarly, Wilson and Particelli’s high school mathematics and physics classes were studying the characteristics of waves. They were concerned about the noise level in the cafeteria so students decided to develop some recommendations regarding what could be done. Students generated 76 questions such as “What type of floor? How does nose travel? and Is there any structural damage?” These questions were categorized into complaints, noise, cafeteria structure, students, and food served.

The students in each class then broke up into small collaborative learning groups to develop plans to answer their questions. In some cases they conducted interviews (Is the cafeteria noisy every day?), or researched reference and textbooks (What rocks can be used to keep warm?), or collected data (What types of trees are in the study plot?), or watched a movie (What does a cave look like?). Students used graphic organizers to guide them through the thinking processes. The types of thinking taught were those important in diagnosing and solving the problem. For example, Wilson’s and Particelli’s students used causal explanation to make judgments regarding noise in the cafeteria, and Owens’s students compared and contrasted characteristics of rocks found in the cave, and Whittaker’s students predicted where they might find the greater number of animals in the study plot. As students continually gathered information in a variety of ways, they judged whether the source was reliable. Students recorded the results of their continued investigations and reflective thoughts regarding the processes in science logs. Students used strategies developed earlier to determine if solutions were effective, should be modified, or further investigated. Wilson and Particelli’s students identified a variety of problems connected to noise reduction in the cafeteria. New issues emerged such as how much will it cost and how long will it take or how will it impact people who have to eat in the cafeteria? Owens’s students devised a plan on how to live for an extended time in a cave using heat, light, sound, rocks, and minerals. Whittaker’s students set up three permanent study plots on campus and are now studying how changes in the surrounding environment are affecting their results over time. In all cases students went beyond their initial problem questions. They all came back to their questions and solutions throughout the school year. Owens’s students even constructed their cave in their classroom. Such lessons demonstrate the ability of teachers and students to take charge of their own thinking.

4. Results

Teachers undertook this project to determine if students could learn at least the same amount of science and mathematics content in a problem-based unit as they learned through standard textbook learning and in the same amount of time. Teachers when interviewed were surprised to discover that they were able to cover the same amount of material, if not more, in approximately the same amount of time. Owens explained:

“I saw the little light bulbs go off when the connections hit home. I think it was good because it really made them think and come up with a question and then figure out a
way to solve it, which normally the information is all laid out for them. What I liked about this is that we did not know what we were going to get. We learned right along with them. I found that students needed as much time to reflect on what they learned as the teachers do.”

Teachers were pleased to report that not only did they feel that their students had achieved an acceptable level of understanding of concepts and principles, but in many cases they went beyond what they thought possible. Whitaker described her experience as:

“It was amazing how the much the students learned as they found the information they needed to answer their own questions. I was concerned in the beginning that this was going to take more time and that they would learn less but the opposite is actually what happened.”

Teachers noted that students developed an initial understanding to the thinking skills and processes that had been integrated into the units. One teacher stated, "I think that a lot of the things they were learning, they were not even aware that they were learning them". The teachers said that they felt the students became more observant and were able to identify relationships and patterns. Overall, teachers seemed confident that their students had “…learned a great deal and benefited from the project. It was new to them". One teacher noted that he overheard his students saying, "I have learned more in this project than any of the current things we are doing in school".

Additionally, students who were randomly selected to be interviewed remarked about the problem-based units that, "everybody was doing a different things and there was no book to follow" and from another student, "It was not just reading out of the book, you actually got to go and do it". All students interviewed said that their ability to ask questions had improved. They said, "it is easier to do now and I can think of them (problem questions) more easily". Donald further explained that he now understands the steps to solving problems when he said, "I can now think about how to solve problem questions. I know how to do it and the steps of how to do it". Students commented that they solved problems over and over again during the units. Erik said, "I can now ask questions that make sense and have more depth". Carl said, "I look at different ways to answer questions now". Three students expressed a deeper understanding of asking questions when they said, "I learned you should ask a lot more questions when you do something that is complicated". Two students seemed to understand science better when they said, "I never knew there was that much stuff to science and I didn't realize how important it was when I started the project".

While student comments did not clearly identify whether or not their ability to solve problems had changed, their comments illustrate that students did have an idea of how to go about solving problems and that their ability to identify or formulate problem questions had improved. There was a dramatic difference between problem identification and the understanding of the steps of skillful problem solving from the beginning of the units to the end of the units as explained by the students in these interviews. Students commented that the units were longer and more involved than what they usually did in science. They began to see that science was not just a collection of facts but rather an in-depth investigation of problem questions to which there were no definitive answers. These aspects are the same as those included in the NOS such as that (a) scientific knowledge is both reliable and tentative, (b) no single scientific method exists, but there are shared characteristics of scientific approaches to science and that (c) creativity plays a role in the development of scientific knowledge.
5. Summary

The overall purpose of this study was to determine the effects of infusing critical thinking skills into problem-based learning in science and its possible effects on teachers’ and students’ understanding of scientific inquiry and nature of science activities. Outcomes of interest include a) understandings and practice of the nature of science, b) changes in instructional behaviors such as the investigation of authentic problems, and c) the teaching of critical thinking skills as well as the basic concepts and principles of science. By situating science instruction within the context of process (i.e. critical thinking skills) in addition to reflection on those skills, process and content learning were enhanced. This led to a broadening of the appreciation of students of NOS and a richer understanding of how science works. This method contrasts with more traditional methods of having students study the NOS by asking them to read about it in a textbook or by having the teacher tell them about it. Through the clustering of generic thinking skills in science, more narrowly and oftentimes incorrect views of science were challenged. In addition, this rich approach of infusion of instruction of critical thinking skills yielded greater results than the more traditional problem-based learning methods.

Little has been provided to teachers regarding the teaching of NOS or inquiry to students. Knowing about inquiry and NOS is necessary but not enough. The approach used in the 1960s and 70s that emphasized hands-on, inquiry-based instruction and implied that by doing science you would learn NOS and inquiry has proven ineffective (Haukoos & Penick, 1985). Likewise the study of the history of science has also proven to be ineffective. An understanding of inquiry and the NOS is best facilitated through an explicit reflective approach (Lederman, 2004) in which students have experiences upon which they can reflect on what they did, why they did it, and what implications the knowledge has for what they have produced. By discussing NOS and reflecting within the instruction, the various aspects of inquiry and NOS, the “doing” of science, is made visible to students. Using the direct teaching of thinking skills in problem-based learning provides a way of teaching in which, for example, alternative explanations of different conclusions are discussed and reflected upon. Students discuss why they have chosen different questions and how their individual creativity and backgrounds influence their choices, understandings and interpretations. Students are taught metacognitive skills. They reflect upon the effectiveness of their thinking and its applications to the science in which they have just participated. By doing this, students understand that they are a part of the practice of science and not just the way science is done in schools.

Problem-based learning in science has the potential to be used in other contexts. For example, this framework could be used to develop cross curricular units or to redesign courses for preservice teachers’ learning of inquiry and NOS. This framework could easily be extended to become a part of college level courses or as a means of redesigning these courses. Ultimately, the most important outcomes of these strategies will be to better prepare teachers who will more effectively teach their students. Future investigations will explore the effectiveness of the process-skills approach on students’ knowledge of science content and the nature of science.
Appendix of selected examples

**Whittaker’s classes selected students’ problem questions and conclusions**

<table>
<thead>
<tr>
<th>PROBLEM QUESTION</th>
<th>CONCLUSION</th>
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<tr>
<td>Is the temperature cooler near the trees or away from the trees?</td>
<td>The temperature near the tree was cooler than one meter away. We think it is because away from the tree gets more sunlight than close to the tree.</td>
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<tr>
<td>Does a larger tree make the air and soil around the tree warmer than the affect of a smaller tree on the air and soil around that tree?</td>
<td>The smaller trees were warmer. The largest trees were second and the medium trees coldest. Trees affect the soil and air temperature. The type of tree and the surrounding trees make a difference.</td>
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<tr>
<td>Does leaf litter insulate the soil it is covering?</td>
<td>Leaf litter does insulate the ground by a matter of 0.5 - 2.0°C depending on the time of day and the duration of the sun hitting the ground.</td>
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<tr>
<td>How many blades of grass were there in each quadrate of the study site?</td>
<td>There were approximately 3,748,148.00 blades of grass in the study site. There was more grass near the woods than in quadrate 2.</td>
</tr>
<tr>
<td>Does the temperature actually affect the number of insects that can be found or just their location?</td>
<td>The insects seemed to be more frequently caught in the sixth trap next to some decaying logs in the woods.</td>
</tr>
<tr>
<td>Which ground cover contains the most insects?</td>
<td>The pine needle by far had the most insects followed by the grass.</td>
</tr>
<tr>
<td>Which animals occur in each quadrate and how does the ground cover affect them?</td>
<td>There were ants, leaves, grass, and clay in most of the pitfall traps.</td>
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**Owens’ classes problems to solve**

1. How will we get enough food to survive?
2. How will we get heat to keep us warm?
3. How are we going to get enough light into the cave?
4. How will we obtain medicine to make us better if we get sick?
5. How will we defend and attach through our knowledge of traps and weapons?
6. How are we going to get around the cave without being harmed or lost?
7. How will we communicate with each other?
8. How will we get enough fresh, clean air?
9. How will we entertain ourselves?
10. How will we defeat the British?
11. How will we find our way around inside the cave?
Owens’ examples of problem questions from organizers

The problem – How might I disguise the cave?
Possible solutions – Hide it with buses and shrubs and trees. Use rocks. Use mirrors to create an optical illusion. Make a decoy cave.
Solution considered – Use mirrors to create an optical illusion.
Consequences – Mirrors may be hard to make from mica. Sun may not be shining. Mirrors can be easily seen. May take a long time to set-up.
Value - The cave will be found and we will be caught.
New solution – Decoy camp by setting it up elsewhere and post guards to warn of approach to cave.

The problem – How might we use the rocks to help us survive?
Possible solutions – Use graphite to communicate. Use rock like pyrite to create a trap. Use mica to keep us warm. Use rocks with sharp edges as weapons.
Solution considered – Use mica to keep warm.
Consequences – Would need to find a lot of mica. It would take some work to get it into the cave. It crumbles easily. It is a good insulator. It would keep the bed clean. It would keep you warm.
New solution – Break up mica and place inside the bed roll for comfort and warmth.

Metacognition Strategy

<table>
<thead>
<tr>
<th>Stage</th>
<th>Metacognitive Level</th>
<th>Teacher Poses Such Questions as…</th>
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<tbody>
<tr>
<td>4</td>
<td>PLANNING ahead for future thinking</td>
<td>How might you do it next time? As you anticipate similar problems in the future, what insights might you carry forth? When else in (this course) (school) (life) (work) might this strategy prove useful? By what criteria will you judge that this is the best way to approach this problem? Why is it important to you…?</td>
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<td>3</td>
<td>EVALUATING the effectiveness of the strategy—before, during and after.</td>
<td>How well did your strategy work for you? “How do you know your strategy is working? What corrections, alterations in your strategy are you making as you….? What will you pay attention to while you are solving this problem to let you know your strategy is working? What alternative strategies might you employ if you find your strategy is not working? Why do you think this is the best strategy? What has worked for you in the past? What makes you think that strategy will work in this situation?</td>
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<tr>
<td>2</td>
<td>Knowing the STRATEGY you are going to use/are using as you do the thinking.</td>
<td>What am I going to use? What approaches might you employ…? As you approach this problem, what metacognitive strategies will you employ…? Are Using: As you consider the steps in problem solving process, where are you…? What patterns are you noticing in these approaches to solving these problems? Did use: As you reflect on your problem solving strategy,…….? What led you to this decision to…….?</td>
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<tr>
<td>1</td>
<td>Being AWARE of the kind of thinking you are doing.</td>
<td>Describe the work you are doing. How did you go about doing it? What was going on in your head when….? What were you thinking when…….? What were you aware of while….? What questions are you asking yourself? While you were solving this problem, what mental processes were you using when….?</td>
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References


