CRITICAL THINKING IN SCIENCE EDUCATION: CAN BIOETHICAL ISSUES AND QUESTIONING STRATEGIES INCREASE SCIENTIFIC UNDERSTANDINGS?

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Abstract

Many North American school districts and post-secondary academic institutions are acknowledging the importance of becoming a critical thinker. Future citizens will need to be informed consumers of technology, science, sociology, and ethics, to name a few. After all, the world has become vastly more complicated, necessitating such skills as reasonableness and logical thinking. By engaging students at a crucial time in their developmental process, we can lay the foundation for good critical thinkers. The purpose of this paper is to examine the importance of critical thinking in science education, both at the secondary and post-secondary levels. Evidence regarding its suitability will be drawn from critical thinking and science education literature, as well as previous studies using bioethical decision-making and generic question stem strategies with middle school and university students.
Critical Thinking in Science Education: Can bioethical issues and questioning strategies increase scientific understandings?

The onset of the 21st Century has been a notable watershed for mankind. Each epoch brings into closer scrutiny that which we have accomplished, and that which remains to be attempted. Interestingly, science is typically the domain that attracts the most attention as it showcases human creativity, intelligence, and tenacity, as well as demarcates paradigm shifts and changes in civilization. But are scientific advancements always for the good? In spite of the seemingly positive changes evidenced in health, economic, and lifestyle contexts, is it not the obligation of educators to ensure that all individuals critically examine scientific development in order to promote active participation as opposed to passive receptiveness? After all, with great change comes great complexity. Equipping the citizens of the next century with the critical thinking skills and dispositions to ensure that scientific change does not direct society, but that society directs scientific change is paramount. Therefore, this paper will discuss science education and the importance of critical thinking, both at the secondary and post-secondary levels. Evidence to support the infusion of critical thinking strategies and issues in the classroom will be presented and discussed.

Science Education

Recent trends in science education have brought into question traditional methods of instruction. Science education can no longer be simply thought of rote recall and memorization of facts, but rather how we come to understand and verify whether the presenting information is true, valid and reliable. Borrowing from psychological literature, science curriculum now emphasizes the importance of the learner’s metacognitive awareness by attending to declarative (i.e., what), procedural (i.e., how) and conditional knowledge (i.e., when).

The origins of this instructional shift stem back to the late 1950’s when
educational research began to focus on the importance of the learning environment and inquiry (e.g., Chiapetta & Adams, 2004; Colburn, 2000), together with the 1980’s focus on the learner and cognitive processing. The result was the constructivist movement with its emphasis on how the individual makes sense of his or her world.

Rooted in the writings of Jean Piaget (1970), his assertion was that humans are innately active knowledge constructors who constantly seek a state of equilibrium between the mind and the environment. For psychologists and researchers alike, Piaget’s work cast new light on cognition and learning. However, critics such as Vygotsky (1978, 1986, 1987) pointed out the absence of human and cultural mediators in Piaget’s theory. Vygotsky argued that symbolic and psychological tools such as linguistics, mathematical systems, and signs all impact the way humans acquire and internalize knowledge. Moreover, parents, teachers, and peers all help to create and alter an individual’s schemata through guidance and interaction. Because of this redefinition of environmental factors, constructivism came to be regarded as both an individualized and a collective experience.

Stemming from constructivism has been the promotion of more inquiry-based science instruction in the classroom (American Association for the Advancement of Science, 2003 http://www.project2061.org/publications/sfaa/online/chap1.htm). Inquiry-based instruction is based on the principle that science educators assist students, with varying degrees of support, to make meaning of scientific knowledge. Students are regarded not as passive recipients of information, but researchers who are required to discover knowledge, skills, and strategies that are personally meaningful and compatible with prior knowledge representations.
Coupled with this has been the implementation of critical thinking practices as a tool to achieve curriculum outcomes. Unfortunately, while inquiry-based instruction has been introduced and supported by the American Association for the Advancement of Science (2003) and the *National Science Education Standards* (1996), many classrooms still partake in content-based instructional approaches. That being the case, the need to address critical thinking in science education must be of foremost importance as it creates the foundation for proficient and ethical consumers of scientific change.

**Critical Thinking in the Canadian Science Curriculum**

In keeping with science education programs around the world, scientific literacy has been identified in the *Common Framework of Science Learning Outcomes, K-12: Pan-Canadian Protocol for Collaboration on School Curriculum* (Council of Ministers of Education, Canada, 1997) as a vital skill necessary for all Canadian students. By definition “scientific literacy is an evolving combination of the science-related attitudes, skills, and knowledge students need to develop inquiry, problem-solving, and decision-making abilities, to become life-long learners, and to maintain a sense of wonder about the world around them”. Moreover, to ensure its development, “students require diverse learning experiences that provide opportunity to explore, analyze, evaluate, synthesize, appreciate and understand the interrelationships among science, technology, society, and the environment that will affect their personal lives, their careers, and their future” (Common Framework of Science Learning Outcomes, K-12: Pan-Canadian Protocol for Collaboration on School Curriculum, p. 4). In order to develop scientific literacy, students require diverse learning experiences that provide the opportunity to infuse critical thinking skills as a means of empowering themselves to better understand the
world about them. Nurturing students to critically examine issues and questions from a societal and environmental perspective supports the concept that science should be approached as an intellectual pursuit, as an activity-based enterprise, and developed as critical thought and inquiry on a daily basis.

Given these statements, the importance of critical thinking is both apparent, and well supported philosophically. As such, the mandate to incorporate higher order thinking skills has made its way into Canadian provincial curriculums with great success. The Alberta Program of Studies for Science Education has incorporated critical thinking skills (http://www.education.gov.ab.ca/k_12/curriculum/bySubject/science/sci7to9.pdf) with clearly delineated provisions for students to critically examine the issues and questions that arise from scientific phenomenon. The four foundations for building learning experiences that address the critical aspects of science and its application include: (1) Science, Technology and Society, (2) Knowledge, (3) Skills and, (4) Attitudes. Of particular interest is Attitudes, since it is seen as the vehicle for implementing the concept of scientific critical thinking and ethics. Here students are “encouraged to develop attitudes that support the responsible acquisition and application of scientific and technological knowledge to the mutual benefit of self, society and the environment” (Alberta Program of Studies for Science Education). Teachers must provide the opportunity to develop the attitudes that support active inquiry. Integral is problem solving and decision-making amid the curriculum content that enhances student’s intellectual development and more importantly, creates a readiness for responsible application of what is learned outside the classroom.
What is Critical Thinking?

According to the literature, critical thinking is the intellectually disciplined process of actively and skillfully conceptualizing, applying, analyzing, synthesizing, and/or evaluating information gathered from, or generated by, observation, experience, reflection, reasoning, or communication (Paul & Elder, 2004). Numerous science education curricula documents consider critical thinking to be a primary component in meeting general and specific outcomes through the promotion of deeper scientific literacy and thought.

While there is no absolute agreement as to what constitutes critical thinking, several definitions attend to the same subset of skills needed to enhance critical thinking instruction in the classroom. They include clarity of thought, intellectual integrity, problem identification and solution, respect for evidence, internal coherence, intellectual standards, metacognition, questioning, deductive and inductive reasoning, argument mapping, and ethical reasoning, to name a few (e.g., Facione, 2007; Fisher and Spiker, 2000; Ennis, 1987; Kennedy, Fisher, & Ennis, 1991; Paul and Elder, 2004). A more recent, psychological characterization is that “critical thinking is the use of those cognitive skills that increase the probability of a desirable outcome. It is used to describe thinking that is purposeful, reasoned, and goal-directed—the kind of thinking involved in solving problems, formulating inferences, calculating likelihoods, and making decisions when the thinker is using skills that are thoughtful and effective for the particular context and type of thinking task” (Halpern, 2007, p. 6). In other words, critical thinking requires higher-order thinking skills that are “relatively complex; require judgment, analysis, synthesis; and are not applied in a rote or mechanical manner” (Halpern, 2007, p. 6).
Given our earlier discussion regarding recent changes in instructional pedagogy, this latter portrayal of critical thinking provides additional support for infusing critical thinking into science education.

**Critical Thinking Instruction**

While there are those who would argue that the processes inherent in critical thinking cannot be prescribed or externally modified, there is evidence to suggest that this is not necessarily the case (Halpern, 2007). Akin to debates in psychology regarding intelligence and its origins (i.e., nature versus nurture), educational psychology has successfully demonstrated that so-called inert processes and abilities are amenable to growth and development (e.g., Dweck, 1975, 1986; Graham, 1990). Through direct and guided instruction, intelligence scores have been shown to improve. This is because the design of intelligence instruments is unable to isolate fluid intelligence (i.e., natural and inherent information processing). Rather, they are heavily based on crystallized intelligence (i.e., social and contextually bound information processing). Similar to the construct of critical thinking, underlying knowledge, skills, and strategies are often contextually predicated (i.e., critical thinking in a specific domain of study; the retrieval of prior knowledge; the application of algorithmic principles). This suggests that vital critical thinking skills can be directly provided to students since they are not exclusively innate processes.

Critical thinking psychologist Diane Halpern concurs with explicit instruction for critical thinking skill acquisition. In *Critical Thinking in Psychology* (2007), she provides specific guidelines for pedagogical practice. Halpern recommends that in addition to the explicit teaching of skills, critical thinking instruction needs to develop the
dispositions for effortful thinking and learning, to increase the probability of
transcontextual transfer through direct learning activities, and to make metacognitive
monitoring explicit and overt.

The importance of explicit instruction and transfer has been similarly noted by the
extensive review of the literature (i.e., 23 “highly relevant” studies, and over 6,500
chapters, articles and papers), they concluded that instruction in thinking skills, in a
variety of different contexts, enhances critical thinking.

**Empirical Support for Critical Thinking in Science Education**

Experts largely agree that the ability to think critically varies with the student’s age
and their ability to understand (e.g., Kennedy, et al., 1991). From a Piagetian standpoint,
children are not able to think critically until they reach the formal operations stage (i.e.,
11 years of age and older). This stage is characterized as embodying such skills as
abstract thinking and the ability to coordinate a number of variables. Although most
normally functioning adolescents can be classified as formally operational, it cannot be
presumed that all are capable of superior critical thinking. This is further complicated
with evidence to suggest that some adults are incapable of simply reaching this higher
cognitive stage (Woolfolk, Winne, & Perry, 2003). Therefore, explicitly teaching and
practicing critical thinking skills in secondary and post-secondary classrooms is neither
redundant nor futile.

In a study with middle years students, Gunn, Grigg, & Pomahac (2006) were able
to demonstrate how explicit instruction of critical thinking skills, combined with
inherently thought-provoking content, could improve critical thinking dispositions, skills,
and strategies. In a year long, quasi-experimental study, 104 Grade 8 students were trained to engage in critical thinking using bioethical case studies. Over the course of the year, three bioethical dilemmas were studied (i.e., organ transplants and their monetary expenses; life-saving medical interventions and religious convictions; and cloning and stem cell use). Two university professors who specialize in philosophy and ethical decision making met with the students to discuss the dilemmas. With each ethical dilemma presented in class, students were asked to independently complete either a visual argument map, a text-based argument map, or a combination of both.

The visual argument map is a concept map that asks students to identify the bioethical dilemma’s “stakeholders”, “possible solutions”, “values”, “positions”, and “reasons for best solution” (see Appendix 1). Visual maps are scored for inclusiveness and accuracy. The text-based argument map includes 10 questions composed as guiding stems. Students are required to identify the most important issues in the presenting dilemma, and support their responses with logical reasoning and evidence (see Appendix 2). Student responses are scored for depth of understanding, suitability/appropriateness of evidence, and the effectiveness/persuasiveness of their position.

Students were also asked to complete Level X of the Cornell Critical Thinking Test (2004) at the beginning of the study, and then again at the completion of the study. In order to ascertain participant preferences for critical thinking activities and instruments, a student satisfaction questionnaire was administered. Finally, the classroom science teacher was asked to journal his observations and thoughts regarding the development of critical thinking skill through the study.

The overall results at the conclusion of this study were quite favorable as they
demonstrated student acquisition of critical thinking knowledge, skills, and strategies. With respect to the *Cornell Critical Thinking Test* (Level X), although the students did not show a significant change from pre-test to the post-test, their scores were significantly higher than the matched norm group sample on the post-test. This suggests that there was some growth in critical thinking skill over the 10-month study period. Additional evidence regarding developing critical thinking skill was found in the analysis of the argument maps. Final results indicated that the students significantly improved in their responses on the visual argument map, and slightly improved in their responses on the text-based argument map.

Perhaps the most exciting results were generated by the Student Satisfaction Survey, as they revealed a growth in vital dispositions, values, and attitudes necessary for life-long critical thinking (Kennedy, et al., 1991; Paul & Elder, 2004). That is, the students reported having a genuine interest in the critical thinking activities and issues. They also believed that they were better able to identify and discuss bioethical issues by the conclusion of the study.

In regards to the perceptions of the participating classroom teacher, he reported that the students were engaging in progressively deeper critical thinking, and he believed that they would now be more likely to actively participate in, and contribute to society. In particular, he saw evidence that many students were developing a genuine sense of the dialectic. That is, they were gaining an appreciation of how diversity of opinion can be an opportunity for growth rather than conflict. Finally, he sensed that the students had now become better able to see how science forces us to make decisions about living in the world, decisions that may not receive universal agreement.
On the basis of these outcomes, there is sufficient evidence to suggest that middle years students can benefit from explicit critical thinking instruction. By using case studies that inherently active higher order thinking skills and scientific inquiry, students are forced to analyze, synthesize, reflect, and reason, to name a few. Presently, many classroom teachers are using bioethics as a means of imparting skill sets and attitudes that give students opportunities to explore ethical questions in critical, yet personally meaningful ways (e.g., Goldfarb & Pritchard, 2006; http://www.bioethics.iastate.edu/classroom.html). In Ethics in the Science Classroom: An instructional guide for secondary school science teachers with model lesson for classroom use (http://www.wmich.edu/ethics/ESC/index.html), bioethics has been identified as a means to stimulate the moral imagination of students; to help them to recognize moral issues; to assist in the analysis of key moral concepts and principles; to encourage individual responsibility; and to assist in the adaptive exploration of issues laden with moral ambiguity and disagreement (Goldfarb & Pritchard, 2006).

Students also benefit from the explicitness of argument maps that guide, direct, and incite critical thinking skills. As noted earlier, metacognition is crucial when engaging students in acquiring critical thinking. By providing cognitive scaffolds that active higher order thinking, students consciously and overtly attain knowledge, skills, and strategies that eventually become internalized and covert as the scaffolds are slowly being removed.

Explicit instruction and scaffolding has also been successfully demonstrated with post-secondary students. Gunn (manuscript submitted) recently examined whether the use of generic question stems could increase expository text comprehension of science
text. Results suggest that by requiring university students to create critical thinking questions, using open-ended generic question stems, memory for, and learning of text materials is significantly improved.

Seventy-three undergraduate students participated in this study. The experiment was conducted in two classrooms. One class was treated as the control condition (n = 38), while the other was the treatment condition (n = 35). At the start of the experiment, students were asked to complete a domain knowledge questionnaire to ascertain prior knowledge of the heart. Scores were calculated and a median split procedure categorized the students as either high or low domain knowledge. Following the questionnaire, each group was explicitly taught the difference between a memory questions and critical thinking questions (see Appendix 3). A brief practice session, to create questions either using generic question stems (experimental condition) or unguided questions (control condition), was followed by the reading of text entitled “Blood”. This text was written to complement the experimental text entitled “Heart Disease”. This would permit links to be drawn during the strategic questioning portion of the experiment. Such supplementary information also facilitates the development of a superior text processing model by enabling a broader understanding of the experimental topic and by providing some prior knowledge to which new information may be linked. The students were then asked to read the experimental text regarding heart disease. This was followed by question construction.

As indicated, the experimental condition was asked to create questions using the six generic question stems. The instructions were to create and answer six questions regarding the heart disease text. Questions could be linked to the blood text (see
Appendix 4). The control condition received the same instructions, only they were instructed to generate their own questions (see Appendix 5). The questions were later coded as being either a textbase model question (i.e., memory of text question) or a situation model question (i.e., learning of text question) (e.g., Kintsch, 1985, 1994, 1998). Following the question construction, students were required to complete a 12-item open-ended post-test. The questions had been previously identified as requiring either textbase model or a situation model comprehension.

Results indicated that those in the treatment group performed significantly better on their overall post-test score than the control condition. They also performed significantly higher on six of the 12 post-test questions, most notably on situation model questions. Interestingly, the low domain/treatment group students benefited the most using the generic question stems, suggesting that where there is an absence of knowledge, using structured scaffolds is advantageous.

The student generated questions were also analyzed. Results showed that the treatment group students created situation model questions significantly more often than their control group counterparts, who created significantly more textbase model questions. In other words, the experimental students created critical thinking questions significantly more often than the control group, despite both groups being instructed on the differences between memory and critical thinking questions.

This study is important for several reasons. Firstly, by employing generic question stems, students are forced to think critically about the material (e.g., Gunn, in press; King, 1989, 1990, 1991). They must make internal connections within the material, create external connections by drawing upon prior knowledge, as well as analyze and
synthesize content in order to pose the question. Simply, students are guided toward a deeper understanding of the material through a Socratic means of generation and elaboration. By posing a question involving familiar or unfamiliar content, the student is lead toward cognitive dissonance, which is the most conducive state for higher-level thinking and information processing (Engestrom, 1987; Mayer, 1989, 1992; Paul, 1990, 1993; Sternberg, 1985, 1988).

Secondly, science curriculum and science textbooks are laden with assumptions regarding domain knowledge. Assisting students by providing methods in which they can acquire knowledge and activate previous understandings is crucial for learning. Through the use of scaffolds such as generic question stems, students are required to reflect upon what they do, and what they do not know or understand (Gunn, in press).

Taken together, these research studies demonstrate how critical thinking can be infused into the science curriculum using both content and explicit strategies. Further research regarding critical thinking as it relates to on-line expository science text (i.e., medical websites), expository science text in the classroom, and bioethical issues in science curriculum is currently being pursued with secondary and post-secondary students.

**Discussion**

The need to develop creative and critical thinkers is growing progressively more important. Technological changes have improved communication, health management, and lifestyle. Unfortunately, rapid change comes with a cost as future citizens will be required to make even greater moral and ethical decisions for themselves, for others, and for the planet. Never has their been a stronger rationale for teaching critical thinking
skills as they offer the greatest chance of success for creating and adjusting to such change. As science educators, it is our responsibility to assist students to think critically about what science is, what it represents, and whether its impact is for the greater good.

The discussion provided herein is an important beginning toward greater accountability. Evidence has been provided to suggest that critical thinking is a necessary component of science education, and that it must be pursued at the secondary and post-secondary levels. By utilizing critical thinking as it pertains to the curriculum and its associated implementation strategies, students can be directly taught to consciously and unconsciously examine issues at a deeper level. These types of skills are not only beneficial in science education, but in all disciplines and avenues of life.

Consequently, critical thinking is not only necessary for intellectual growth, but also for making sense of our world.
References


Appendix 1

STAKEHOLDERS

Reasons for Best Solution

Possible Solutions

ISSUE

POSITIONS

VALUES
Appendix 2

BIOETHICAL ISSUE STUDY
Critical Thinking Mapping

1. The **issue** presented here is

   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________

2. The **stakeholders** identified are

   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________

3. The **values** that need to be considered are

   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________

4. I feel these **values** are important because

   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________

5. My **position** on this issue is

   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________
   ___________________________________________________________
6. **I believe this position** for the following reasons (list 3)
   __________________________________________________
   __________________________________________________
   __________________________________________________
   __________________________________________________

7. I feel these **reasons are good reasons** because (list 3)
   __________________________________________________
   __________________________________________________
   __________________________________________________
   __________________________________________________

8. Others might feel **they are not good reasons** because (list 3)
   __________________________________________________
   __________________________________________________
   __________________________________________________
   __________________________________________________

9. I might **disagree** with them because (list 3)
   __________________________________________________
   __________________________________________________
   __________________________________________________
   __________________________________________________

10. Given the above discussion, **my final position** on this issue is
    __________________________________________________
        __________________________________________________
Appendix 3

MEMORY QUESTIONS

-Memory questions ask you to recall information that you have read.

-The information can be found by simply looking back at a specific part of the text or at a specific sentence.

-Questions and answers are easily available by looking at the text. They are recorded explicitly within the text and they can be memorized.

Examples:
1. Describe what Indonesia is like geographically?
2. What are the primary products made in Korea today?
3. Where do many Indonesians live?

CRITICAL THINKING QUESTIONS

-Require you to explain concepts or relationships between ideas, to apply the information that you have read to other situations, to draw conclusions based on what you have read, to support your ideas based on what you have read, etc.

-Critical thinking questions ask you to think about what you have read and to apply that information to other parts of the text or to what you already know about a topic.

-They ask you to critically examine, and not just remember or repeat what you have read.

Examples:
1. Which country is farther north and higher in elevation?
2. What industries do you think Indonesia bases much of its economy on?
3. Based on what you have read about Indonesia and Korea, which country has a better standard of living?
Appendix 4

Question Stems

Instructions:
1. You are to generate 6 questions using the generic question stems.
2. You are to use each question stem only once.
3. Be sure to answer your question.
4. If you are pressed for time, create your question and return to answer it later.
5. You may refer to and create links with the text entitled “Blood”, but your task is to create questions using the “Heart Disease” text.
6. You have 20 minutes.

- What do you think might occur if.....? answer:........
- What information do we already have about......? How does it apply to ......? answer:........
- Are there any differences between..... and .....? Explain.
- ........appears to be a problem because........ What are some possible solutions?
- The author(s) states that “.................” Explain why this statement is true or false.
- Compare.....and/with ......in regards to......... Explain your answer.
Appendix 5

Questioning Reminder

1. Carefully read the text entitled “Heart Disease”.

2. Once you feel that you understand what you have read, create 6 questions. (Suggestion: To help you think of good questions, pretend that you are going to ask another student questions about what you have just read.)

3. Be sure to answer your question.

4. If you are pressed for time, create your question and return to answer it later.

5. You may refer to and create links with the text entitled “Blood”, but your task is to create questions using the “Heart Disease” text.

6. You have 20 minutes.