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Defining and Measuring Critical Thinking in Engineering

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Abstract

Critical thinking is generally recognized as an important skill, and one that is a primary goal of higher education. However, there is surprisingly little in the literature regarding critical thinking in engineering. This paper describes two pilot studies. A mixed methods study found that graduate engineering students performed worse than undergraduate students on a standard critical thinking instrument. This difference is explained through the two groups' familiarity with test-taking. In a qualitative study, engineering undergraduates were interviewed about how they use critical thinking. It was found that their descriptions were more complex than typical definitions in the literature. Overall, the results point to a need to further investigate what critical thinking means for engineering.

Keywords: Critical thinking; higher order thinking; critical thinking in engineering

1. Introduction

Development of critical thinking skills is generally recognized as an important aspect of undergraduate education. As pointed out by Mason (2007) much of the rhetoric regarding education and its reform revolves around teaching students to think and question critically. Surveys show that well over 90% of faculty believe critical thinking is one of the primary goals of higher education (Gardiner, 1994; Sax, Astin, Korn, & Gilmartin, 1999). Most definitions of critical thinking are based on identifying specific abilities that seem to be associated with critical thinkers and provide general definitions (Dressel & Mayhew, 1954; Ennis, 1987; Facione, 1990; Iowa, 1989; Stein et al., 2010). Less work has been done to define critical thinking specifically within the context of engineering. For the most part these studies have considered critical thinking in the context of engineering problem-solving (Cloete, 2001; Lunt & Helps, 2001; Mina, Omidvar, & Knott, 2003). A comprehensive overview of critical thinking in engineering cannot be obtained from the available literature, which is somewhat

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surprising given its perceived importance. What is missing from the literature is an understanding of what critical thinking is in engineering and how students use critical thinking. This study begins to address these issues by examining how critical thinking is practiced by engineering students and how it might be measured. The specific research questions that guided this study were: 1) What are the processes students use to solve critical thinking problems? 2) What do students believe that critical thinking is? 3) Is there a difference in critical thinking skills between undergraduate and graduate engineering students?

2. Methodology

This paper describes the results from two pilot studies. The first was a mixed method study which examined the differences in critical thinking skills between undergraduate and graduate engineering students. The second was a qualitative study in which undergraduate students were interviewed about how they used critical thinking in engineering and their everyday lives. Details of the methodology for each of these studies are given below.

2.1. Mixed Methods Study

The CCTST Form 2000 was administered to 12 graduate students in Materials Science and Engineering who had passed the PhD qualifying exam, and 13 undergraduate juniors in Materials Science and Engineering at the same institution. Participants were limited to students in the Materials Science and Engineering Department, and to students whose prior education was primarily in the US, in order to reduce variability in the sample and increase the likelihood of finding differences between the two groups despite the small sample size. Undergraduate students were recruited by a general advertisement through email, and the first 13 responses were accepted as participants. This approach was not effective with the graduate students (only one graduate student responded to the general email), and so graduate students were recruited by specifically inviting individuals selected randomly from the population of students who met the qualifications. The CCTST was administered several different times and the test manual procedures were followed in all cases. The most important aspect of the procedure for this study is that there was a 45 minute time limit for completing the instrument. Participants were paid $20 for participating in the study.

Subsequent to administering the CCTST, participants were contacted by email and asked to reflect on their experience taking the instrument. A total of 8 undergraduates and 10 graduate students responded. Codes were developed out of the responses by identifying major themes articulated by the students.

2.2. Qualitative Study

The participants in this study were undergraduate civil engineering students at a large public university. Participant characteristics are given in Table 1. Alice and Jose are older students. Alice is married with two young children. Jose is 33 years old, and served in the military before attending school. Interviews were conducted in which the students were shown four different problems taken from the California Critical Thinking Skills Test (CCTST), Form 2000. The first two problems were given exactly as on the CCTST. The second two problems were similar in nature to the first two, but they were given without the multiple choice answers. The exact questions cannot be disclosed because of requirements imposed by the publisher on the use of the instrument. However, they can be described generally as non-engineering problems that are based on everyday occurrences and do not require specialized knowledge. The questions were matched to be similar in type. Two of the questions (one with the answers provided and one without the answers provided) could be classified as “logic puzzles” that require, for example, placing items in an order based on certain requirements. The other two problems were ones in which a situation was presented and the students needed to come to some type of conclusion based on the evidence.

The interviews were semi-structured, with questions focused on the approaches the students used to solve the problems and general questions about how they have used critical thinking, both within and outside of engineering. The interviews lasted 40-60 minutes, and students were compensated $20 for their participation. The interviews were recorded and transcribed verbatim. Analysis was conducted using thematic analysis. As suggested by Grbich (2007) transcripts were examined for statements that related to the research questions (p. 32). These statements were then grouped into themes through a constant comparative process.

Table 1. Participant characteristics

Name*	Sex	Race	Year of study	GPA
Alice	female	white	junior	3.69
Mike	male	white	junior	3.36
Angela	female	Hispanic	junior	3.82
Luis	male	Hispanic	senior	3.02
Jose	male	Hispanic	senior	3.20

*Names are pseudonyms.

3. Findings

3.1. Mixed Methods Study

Table 2 provides the descriptive statistics from the CCTST for the two groups. Surprisingly, the undergraduates scored higher than the graduate students, scoring on average 3 points higher. As it is usually interpreted, this difference would imply that the undergraduates are more skilled at critical thinking than the graduate students. However, further analysis reveals that the difference is caused by the graduate students answering fewer questions within the time limit. A total of 12 of the 13 undergraduates were able to complete the instrument within the time limit, while only 3 of the 12 graduate students were able to complete it. Table 2 shows that on average the graduate students answered 3 fewer questions than the undergraduates. When the percentage of correct items out of the total number of items answered is calculated, the difference between the two groups is eliminated, with both correctly answering approximately 70% of the items.

Table 2. Results from the CCTST (Numbers are the mean responses.)

	Undergraduate students	Graduate students
CCTST index[a]	24.15	21.17
Number of items answered[a]	33.92	30.92
Percentage of items correct[b]	71.23	68.70

a: Difference between the two groups is significant at $p<0.05$.
b: Percentage of correct answers out of the total number answered.

In order to understand the difference in the ability of the two groups to complete the instrument, the students were asked to reflect on their experience. The only guidance they were given was that there was a desire to explain a surprising difference in the ability of some students to complete the instrument. Table 3 shows the general codes developed from the responses, and the number of responses that could be identified with each code. It should be noted that in Table 2 a single participant's response may be coded in more than one category.

Some clear distinctions between the two groups emerge from Table 3. Six graduate students commented on some aspect of the difficulty they had in analyzing the items and the time they spend trying to select an answer (codes 1 and 2):

…several of the questions could have been answered in more than one way depending on how the paragraphs were read… I remember marking at least four or five questions that seemed to have more than one correct answer. Knowing that there could be only one correct, I spent a great deal more time with these questions than expected. (Graduate student).

I remember many of the questions required accurate "book-keeping" of the situations described. I know that on numerous questions I had to reread the descriptions, sometimes more than twice. (Graduate student).

Table 3. Coding of participant responses to the request to reflect on their experience of taking the CCTST. (The numbers indicate the number of each group who provided a response that could be coded in that category.)

	Undergrad	Grad
1. Hard to choose answers, spent time deciding.		3
2. Questions were complicated, needed to read carefully		3
3. Tried not to stay with any question too long, made best educated guess.	3	
4. Long time since I took a written test.		3
5. CCTST was similar to high school or undergrad experience.	2	
6. Surprised when time was up.		2
7. Use of test-taking strategies.	1	2
8. Different attitude towards exams or ability to think as grad vs. undergrad.		4
9. Hard to choose answers, no indication of strategy.		2

In complete contrast, three of the undergraduates commented on taking an opposite approach (code 3):

On the ones that I couldn't figure out an answer immediately I simply made an educated guess based on what I knew. I left the test thinking it had several challenging problems that could really confuse you if you tried to spend a bunch of time on them. (Undergraduate student)

Another clear distinction was in how they saw their recent experience with exams affecting their performance (codes 4 and 5):

I feel that the test was remarkably similar to the SAT reading comprehension section... Also I have been enrolled in some classes that have had a basis of reading and writing, which I think helped. I felt that the test was based on knowledge that I had learned throughout high school. (Undergraduate student)

At the onset of the exam, I realized that it had been years since I had taken a "standardized test" such as the SAT or GRE. I had to remind myself of the time limit and to pace myself. (Graduate student)

Another theme that emerges comes from the graduate students who commented on how their thinking has changed since they were an undergraduate (code 8):

I have found that learning does not stop with studying, but often connections are made while taking the exam. I can't say I enjoy taking exams, but I have developed a newfound "respect" for them. As an undergrad I would take the exam, answer the questions the best I could at the time, and leave without another thought. I looked at it as the last step before the break. It seems in graduate school, I'm more apt to take my time reading the questions *and thinking through my answers, not just scribbling the first thought and moving on. Of course this does not necessarily mean I get more questions correct, but I do put more thought into my work.* (Graduate student)

...there is an actual metamorphosis that we make from being an undergraduate to a graduate student. From being an undergraduate, the curiosity to learn new things and time you spend on expanding your mind is not as mature as when you are a graduate student. I feel that becoming a graduate student, compels me to delve deeper into understanding what is going on and why. When the test was administered, I feel like I was driven to take this test seriously and try to analyze what these questions/problems were relaying. So basically when I was an undergraduate I didn't feel like I took things as "serious" as I do, nowadays. (Graduate student)

3.2. Qualitative Study

Five primary themes associated with critical thinking were identified from the interviews: identifying the problem and information, organizing information, using prior knowledge, using opinion, and making decisions. Each of these themes is discussed further below:

<u>Identification:</u> All of the students described the need to identify the purpose of the problem and the relevant information needed to solve the problem. This process took several forms, ranging from simply reading the problem statement to specifically targeting certain information. For example, in solving one of the problems Mike said “I’m just reading it…and then I had to read it over again…I’m just trying to process what I just read.” Similarly, Alice stated that, “And as soon as I understood the direction that it was going I realized, OK, I need to read this very carefully, and so I reread it again, and then I understood now, even better, what I need to be looking for.” Jose explicitly discussed the need to understand the purpose of the problem. “…first we have to see the purpose of the question. If it is to test what my prior knowledge is, or if it is to test my reasoning based on the question.” In solving one problem, Luis noted that it was necessary to filter the information provided to come to an answer. “…it’s just secondary data that you don’t need…” Careful reading and understanding of the problems appeared to be the first step used towards solving them.

<u>Organizing information:</u> Another general skill that was used by students was strategies for organizing the information presented in the problems. This organization was done in a variety of ways. Luis used both mental representations and visual representations of the information: “…just trying to picture things in your head and then how would you solve a problem...”, “…this little diagram that I drew here…’cause that helps your visualize as well.” Mike, in contrast, used only mental representations of the data: “I started drawing a linear relationship in my head.” “I just went straight through trying to notice the different ratios.” On one of the multiple choice questions, Alice provided a visual description of the mental process she used to select among the choices: “Even though I’ve thrown those out, they’re [choices A and B] still kind of on the side”,”…when I finally make my decision then…I feel very sure about C…so now D is now in the margin for me”, “They’re [choices A and B] in the garbage.”

<u>Using prior knowledge:</u> Some students expressed that they did not look solely at the information in the problem, but also looked to prior knowledge that might help them. Jose felt that your level of prior knowledge affected how you might answer a question. “I know, because I have seen the word maybe a thousand times by now…But if we bring [in] someone that [does] not…know[s] anything about the problem, this would not be enough information.” For Alice, the ability to use knowledge is a key component of critical thinking: “I had to really like, reach in and kind of pull out something that maybe wasn’t right on the paper. And when you have to like go through your filing cabinet of stuff, then that would be a lot more critical.” Mike saw critical thinking in

everyday life as occurring "on the basis of everything that you've experienced and everything that shaped you to this point in your life."

Using opinion: Although several students recognized that opinion could come into play when solving the problems, they used opinion in different ways. For Alice, her personal opinion was something to be wary of: "I mean, obviously these problems all deal with the most logical answers, so you have to separate your opinion from what you're trying to put on the paper." In contrast, Mike appeared to accept the use of his opinion as providing a means to get the answer: "This first one led me to the choice…because I thought that that was probably a cause of it." In discussing critical thinking in general, Mike placed a large emphasis on the role of opinion: "What's true to you and what's not true to you I think you think critically about those issues." "I guess you just think about what's true to you, what's ethical, what's right to you."

Making decisions: All students stated that their answers needed to be based on sound decisions that could be justified. Mike's approach to the problems was to "just reason it, make sure that what I've got down, my answer, makes sense to me." Even when the problem did not involve any complicated knowledge, according to Alice justifying the final answer was important: "It's not that hard of a problem, but I have to really think about the fact that I could have more than one answer…and that I have to come up with that on my own, and be able to stand behind it." Angela felt that making decisions is at the heart of critical thinking. When asked if people can function without doing critical thinking, she answered, "Yeah. But that's when people don't make good decisions." Jose emphasized that for him critical thinking is the development of a process that leads to a decision. "Now you're [making] a conclusion based on an analysis…" Similarly, Luis discussed the process of arriving at a conclusion, but in his case the emphasis was on choosing the path to arrive at that conclusion. "…your…goal is to get to one answer,…which route are you gonna take to get there?"

In addition to these themes, the students discussed what constitutes critical thinking. Here the conceptualizations varied widely. Alice believed that critical thinking required you to think in a new way. If you use a known algorithm to solve a problem, for her that is not critical thinking. Jose felt that critical thinking was the development of a process to solve a problem. Thus, even if you use an established algorithm, that is still critical thinking because you are using a process that had to be created. Luis had an intermediate view, stating that a "plug and chug" problem could contain critical thinking if you thought about what the answer means and did not simply accept the answer as given.

4. Conclusions

Taken together, the results from these two studies point to the complexity of critical thinking and the limitations of our current understanding. The mixed methods study shows that critical thinking cannot be operationalized in a simple instrument. The difficulty is that, to make critical thinking amenable to measurement, instruments treat critical thinking as a set of discrete skills which can be measured separately. A person who can accomplish each of these skills is assumed to be able to think critically. There is also the issue of whether critical thinking is more appropriately measured through a recognition task, as in this study, or through a production task. The results from this study suggest that the CCTST, and by extension similar instruments, actually measure test-taking ability and not critical thinking.

Contributing to this difficulty in measurement is the complexity of critical thinking as brought out in the qualitative study. It is clear that critical thinking as practiced is much more complex than most conceptualizations imply. Rather than a discrete list of independent skills, critical thinking includes a series of feedback and interactions among the skills.

Future work is needed to more clearly understand what constitutes critical thinking in engineering. We are continuing the work described here with a qualitative study that will examine expectations for critical thinking among faculty, how critical thinking is enacted in practice, and how critical thinking in engineering differs from critical thinking in other fields such as humanities. Ultimately, our goal is to create a model for Engineering Critical Thinking.

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