A thematic analysis on critical thinking in engineering undergraduates

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Abstract
This qualitative research paper examines the meaning and enactment of critical thinking for engineering undergraduate students. Though critical thinking is considered an important topic in the engineering community, research on the topic is limited to mostly measuring critical thinking in the classroom and definitions used are not empirically based. Thus, in this paper we seek to provide an initial exploration of what critical thinking is in engineering. We address the following research question: How do undergraduate engineering students perceive and enact critical thinking? Semi-structured interviews were conducted on the enactment of critical thinking and analyzed using a thematic analysis. Main themes that arose from the interviews included: difficulty articulating critical thinking ideas, relating critical thinking to engineering course concepts (especially problem solving), communicating with others, disposition to think critically, metacognition, challenges of critical thinking in the classroom, and critical thinking varying in other disciplines and majors. Problem solving concepts prevailed in the many of the themes. Although themes connected with many of the ideas present in current definitions of critical thinking, most students did not mention concepts of clarification, credibility, generalization, or recognizing assumptions. Participants also emphasized a broader idea of communication and stronger reliance on real world context in critical thinking than previously established by critical thinking definitions.

Introduction
Academics value the importance of critical thinking in the development of any student. However, in their book, Academically Adrift, Richard Arum and Josipa Roksa revealed the notion that critical thinking may not be learned by students in undergraduate programs. After emphasizing how little students gain in the four years of college, Arum and Roksa stated more generally that: “While [students] may be acquiring subject-specific knowledge or greater self-awareness on their journeys through college, many students are not improving their skills in critical thinking, complex reasoning, and writing.” (p. 36) Before their book created a renewed interest in critical thinking, ABET EAC criteria and the NAE report The Engineer of 2020 created criteria and attributes that focused on what engineering students needed to do for the future. The NAE outlined the following important attributes: “strong analytical skills, creativity, ingenuity, professionalism, and leadership.” These attributes and the EAC criteria do not identify critical thinking directly; however, the listed skills relate to common ideas of critical thinking. Due to this drive for improvement, many engineering programs and departments have begun to incorporate critical thinking into their goals for student outcomes or into their mission or vision statements. It is important to study how these goals can be met and what is being done in higher education to achieve them.

Many definitions of critical thinking exist. One of the commonly used definitions is that of the “Delphi Report” which defines critical thinking as “purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or contextual considerations upon which that judgment is based.” Mason’s simplified framework of critical thinking, based on many of the existing philosophical approaches to critical thinking, includes the following aspects:
• **The skills of critical reasoning (such as the ability to assess reasons properly);**
• **A disposition, in the sense of:**
  - A critical attitude (skepticism [sic], the tendency to ask probing questions) and the commitment to give expression to this attitude, or
  - A moral orientation which motivates critical thinking;
• **Substantial knowledge of particular content, whether of:**
  - Concepts of critical thinking (such as necessary and sufficient conditions), or of
  - A particular discipline, in which one is then capable of critical thought. (pp. 343-344)

Most definitions of critical thinking are not empirically based and they are rarely specific to engineering. Recently critical thinking experts created guides on critical thinking. Paul and Elder created a ‘mini’ guide for critical thinking in the classrooms and expanded their work to a guidebook for critical thinking in engineering called Thinker’s Guide to Engineering Reason. Following up on Paul et al. and the work of the critical thinking foundation, Van Gyn et al. also created a guideline for critical thinking for engineering. These were created based on common definitions and engineering concepts, but not based on empirical research. Although these guides allowed operationalization in some recent engineering studies, critical thinking research in engineering is generally conducted without a structured definition of critical thinking and is most commonly used to simply measure critical thinking in the classroom.

The few definitions or structured guides of critical thinking that are empirically based are built from receiving input from a variety of faculty, including engineering faculty. However, research on the meaning or ideas of critical thinking for students is not present in literature. Critical thinking is often incorporated without gaining student input, especially on how they best enact critical thinking. How do we know if students are enacting and understanding the critical thinking that faculty members and departments intend to instill? Are students understanding and learning the same critical thinking as defined by these guides, definitions, or faculty members? Do students enact critical thinking only in particular environments or situations? Understanding students’ perception and enactment may create a foundation for more efficient implementation of critical thinking in the future. To answer these questions and help students learn more effectively, gaining student input and understanding student perspectives is necessary.

Thus, in this paper we seek to provide an initial exploration of what critical thinking is in the engineering classroom. This research paper examines the meaning and enactment of critical thinking for engineering undergraduate students. We address the following research question: How do undergraduate engineering students perceive and enact critical thinking?

**Methodology**
This study is the pilot phase of a larger project aiming to understand critical thinking for students and faculty in humanities and engineering. Since this is a part of the work of a larger study only one discipline and 5 students were examined. Further disciplines will be studied as part of the full study. In this paper, we examine the enactment and meaning of critical thinking for materials science and engineering students. Students were selected by requesting participants in a required senior materials science and engineering course and asking students to email back if interested. The first five students to respond were selected. Semi-structured interviews were conducted with
these five students. These interviews focused on the ways in which students used critical thinking in their engineering classes and what critical thinking means to them. Interviews were analyzed using a thematic analysis. Statements in the interview transcriptions were coded with descriptive labels. These codes were then categorized with similar concepts. When more than half the students expressed similar concepts, the category became a major theme. This includes concepts of opposing views. For instance in the theme critical thinking varying in other disciplines and majors, three students mentioned some aspect of critical thinking in different disciplines but not all had the same view. One student said critical thinking was the same for everyone with just a different knowledge base, another student felt there is a difference in thinking between engineering majors, and a third student had a view somewhat in between these two. Based on these related or opposite aspects, the general idea was supported by more than two students and a theme was created. However, if a concept was only mentioned by two students and no related or opposite ideas mentioned, the concept was not considered a theme at this time. With further data collection and analysis of other students more themes may arise.

**Findings**

Many themes appeared in the data. The main types of themes include the following categories: difficulty articulating critical thinking ideas, relating critical thinking to engineering course concepts, communicating with others, disposition to think critically, using metacognition, challenges of critical thinking in the classroom, and critical thinking varying in other disciplines and majors.

*Difficulty articulating critical thinking ideas*

Many of the students expressed confusion and felt unsure when addressing thoughts on critical thinking. They showed poor ability to articulate how they used or viewed critical thinking. Interviews included contradicting thoughts and direct statements about not knowing how to express their views. For example when one student discussed his way of reasoning, he stated, “Okay. Um, (pause) well, I mean, you have to, well, I mean, I consider the multiple aspects that, um, are, it’s hard to phrase, let’s see.” Another student struggled to verbalize her thoughts when discussing teaching critical thinking. “So I think, I think they’re teaching something in a fashion that makes sense to people. I’m not sure how to explain what I mean. Um. (pause)…”

*Relating critical thinking to engineering course concepts*

Although students struggled with articulating their thoughts, students did tend to relate ideas of critical thinking to engineering concepts they deal with in the classroom. These engineering course concepts include: applying a framework/plan; weighing, selecting, and testing options (selection and design); using background knowledge; and using problem solving. For instance one student explained the critical thinking process in a design course as:

*There’s a coach but no one tells you what to do or how to solve the problem. You’re expected to understand the problem, come up with possible solutions, select those solutions, or select the best couple solutions, test them and you know, at the end of the year design the products.*

Every student directly mentioned needing a knowledge base or background. For example, “And then start working off your basis of knowledge, you know, what do you know for the material
selection process, you know, what materials just come to mind when you think of things, start looking into those.”

Many of these course concepts confirm the students’ idea that critical thinking was similar or equivalent to problem solving. Though students believed in many different styles of problems and answers, including a right answer and an opened-ended problem with many or no answers, problem solving in general was mentioned by every student. As one student explained, “Um, I mean, it seems like I said to me critical thinking is just like, you know, problem solving. It’s taking everything that you know and applying it to narrow down to your solution.” Problem solving included five sub-concepts: figuring out what the problem is, figuring out why something is happening, solving in an orderly way, applying to a real world context, and reaching a conclusion/solution. Students found defining the problem as the first step:

I think like again this is at least in my mind the way I think about it, um, the first thing is to understand the, the problem or whatever it is that you have observed uh and then when you’re developing um, the plan on how to fix it you want to address whatever the root cause is. So that’s why understanding the problem is so important.

Many students mentioned figuring out why something occurred: “So you already have some idea of where you’re going. You already may know what you’re looking for but something might shock you or surprise you and then you have to go back and figure out okay, why did this occur?” Participants also valued applying problems to the real world: “Like because it’s a real world problem and I think the only way you can train people to solve real world problems is by giving them real world problems.” Students also shared a similar idea of the final step to critical thinking, reaching a conclusion or solution. As one student stated, “Well, I would define critical thinking as the employment of reason in order to reach a conclusion especially in regards to problem solving.”

Disposition to thinking critically
Beyond what was taught in the classroom, many students saw the necessity of particular personality traits. Some students mentioned needing curiosity or interest or desire to think critically. One student mentioned: “Um, like practical hands-on projects because it would get someone interested in it and you like make them feel like they’re actually doing something to motivate them to actually think critically.”

Using metacognition
A few students also discussed having the ability to think about their thinking or using self-checking as an important trait towards critical thinking: “Meta cognition, like um, like is, is my way of thinking correct? Like is this, is this process actually effective and um, will lead to correct answer or that kind of thing.”

Communicating with others
Students believed communication to be important for practicing and using critical thinking. For example one student stated: “I mean, I guess it’s always good to explain to someone why you’re thinking the way you think because like you could just make an informed decision, but if you can’t tell someone why then that decision probably won’t become a reality.” Not only is
explaining to others important, but discussion with others and learning from them also holds value to the participants. For example, one student explained this interaction:

So I think yeah, pulling in people from other disciplines, both engineering and even non-engineering. They might say something that you think why wouldn’t that work but you just would’ve never thought of it because you’re, you know, your mind is already kind of going through the steps that you’re used to ...

Critical thinking varying in other disciplines and majors
Learning from others was often achieved by interacting with students from different disciplines and majors. A few students believed other engineering disciplines and non-engineering majors to have differences in the process of thinking. For example:

Well, I think that engineers in general when they’re all grouped together, think in a very mechanical way, I mean mechanical engineering, a pun intended I guess. But um, but you know you think of okay what equation can I use or what mechanism should I apply to this. Or um, you know, things like that. Um, but I think when you start to get into the things that people don’t know as much about which is materials in general, then you start to run into, okay, let’s think about this more in a simplistic way, or let’s think about this more in a scientific way, but for a lot of engineering disciplines, it’s more of, you know, the answer’s out there and we just have to figure it out.

However, others believed that critical thinking was the same for everyone with just a different knowledge base. As mentioned by one student:

I don’t, I don’t know if there are necessarily critical, you know, critical thinking or thinking differences between the two skill sets. Like I think the skills to answer you know, like a psychology exam and answer an engineering exam, not like knowledge-wise but like how to do it are maybe the same. It’s just that people’s background and you know, influences them to see them differently.

Whether the students saw that critical thinking was the same or different between majors, many agreed with the previous quote that background had an influence on how a student thinks.

Challenges of critical thinking in the classroom
The students also expressed views on the way critical thinking should be taught, indicating that critical thinking seems to be challenging for their instructors to teach but that it is important, especially for ‘real world’ work after academia.

They believed that the way to teach critical thinking was through engagement: “Um, well, like for example, this is a really simple one but if they have a, ah, they’re teaching and they, they kind of ask the question like okay, so what comes next …” Also this can be done through faculty guidance or coaching as one student explained:

Exactly, exactly. And so it’s important to kind of help them along. I think they—I guess what I’m trying to say is um, if you give someone up there a mechanical problem they’ll solve it. They may gain very little, not lose really anything so it’s kind of a net zero loss. Um, if you give someone a really abstract thing and they just kind of shut down then that’s a loss and if you give them something abstract but they actually kind of work at it and you help them along then that’s a gain.
However participants found that explicit teaching and assessing of critical thinking was challenging in the classroom:

...um, so it’s, I think [implementation of critical thinking is] pretty rare because assignments, it seems like they’re hard to design with like critical thinking embedded in them. It’s definitely, like even just using the textbooks like most textbook questions are just the, more of the equation type. Some are not so much. I’ve seen some that aren’t but ah, typically, I think that critical thinking questions like the ones that really make you think, ah, I mean, they tend to take longer.

Conclusions
As stated, students had difficulty expressing their views on critical thinking. Ahern et al. similarly found that engineering faculty had difficulty with articulating critical thinking.\textsuperscript{34} Ahern et al. also indicated that critical thinking is not explicitly discussed or addressed in engineering classes by these faculty.\textsuperscript{34} This fact that faculty do not, or possibly cannot, make critical thinking explicit may explain why the students in this study experienced difficulty expressing their thoughts. Lack of direct exposure and direction by faculty may hinder students’ ability to articulate and understand their own ideas on critical thinking.

Students coped with this gap by relating critical thinking to engineering concepts, including using background knowledge and resources, criteria selection, and the engineering process of approaching problems. These concepts, though usually based around class context and exercises, connect to some general ideas of critical thinking including: identifying problems, comparing ideas, evaluating, discovering alternatives, drawing a conclusions, supporting with relevant and adequate evidence, and involving content knowledge.\textsuperscript{14,15,20–22,24,31,33,35} It is important to mention that many of these critical thinking concepts from the participants and the related concepts from literature connect to problem solving as defined in the literature. Problem solving based on Woods, for instance, includes engage: I want to and I can, define-the-stated problem, explore, plan, do it, and look back.\textsuperscript{36}

There are criteria beyond engineering concepts and problem solving useful for critical thinking. Non-engineering concepts that exist in the literature that were confirmed by the students included metacognition,\textsuperscript{12} usually indirectly mentioned in the literature as part of the ability to reason, and disposition.\textsuperscript{16,24,37} However, though present for a majority of the participants, these concepts were not unanimously mentioned. Also Mason’s idea of a moral disposition was much less apparent, not appearing as a theme from these interviews.\textsuperscript{21}

Communication with others also helped them solidify how they learned to think and broadened their abilities to approach problems. The forms of communication, learning from others and explaining to others, are not often included in formal definitions of critical thinking. The Delphi report does include the idea of explanation and some other experts mention argumentation or presentation.\textsuperscript{15,20,22,24,31} Willingham’s definition includes argumentation mentioning “seeing both sides of an issue” and “demanding backing of claims.”\textsuperscript{13} However, argumentation and presentation are not necessarily equivalent to discussion or learning from others.

As discussed, many main themes connected to the critical thinking concepts in literature; however, some concepts were not prevalent in the data. Missing critical thinking concepts
include: clarification, credibility, and recognizing assumptions. One or two participants discussed these ideas but not a majority of the participants. Most students did not discuss looking into the credibility of sources or recognizing assumptions during their problem solving process or design project work.

Participants highly valued certain concepts beyond those previously discussed in literature. From the students’ perspective, faculty teaching through a real world context and coaching the students promoted learning critical thinking. Existing literature does not emphasize these concepts when discussing the critical thinking process. Critical thinking in academia and in practice is valuable to these students, but in order to learn and understand critical thinking better, they need engagement from faculty and an emphasis on critical thinking from faculty and in the curriculum. Connecting critical thinking more explicitly to engineering concepts may help future students better understand the meaning of critical thinking and learn it more effectively. Future work will expand upon this study to include a grounded theory on critical thinking in engineering for both students and faculty. This pilot study was limited to one discipline; however, the future work will include interviews with students in other engineering disciplines and with the respective discipline’s faculty members.

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