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Exploring the role of engineering judgment in engineering education through writing praxis in a 3rd year systems engineering writing-in-the-disciplines [WID] course

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Abstract

Critical thinking is central to the rationale of university education and engineering education. Critical thinking does not have a single agreed operational definition in engineering education. One useful definition described by Ahern et al (2019) quoting Facione (1990) is: "[critical thinking] is a '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 judgment is based.'" In this paper, we describe engagement with a writing assignment for undergraduate systems engineering students intended to foreground engineering judgment in student writing processes from the perspective of an instructor and an undergraduate student. We conduct a reflective autoethnography **to construct key elements of the ways both student and instructor participate in the construction of engineering judgments through the course's writing processes**. This reflective essay advances the possibility for engineering judgments constructed in well-designed writing assignments to improve critical thinking capabilities. Judgment is implied by by many common interpretations of critical thinking in engineering. Understanding critical thinking in engineering education is incomplete without closely exploring engineering judgment. Critical thinking, or improving critical thinking, is considered an urgent need because engineering graduates are often considered deficient in these skills upon entry to the workplace. Claris and Riley (2012) discuss this "situation normal" where engineers often possess strong logical thinking skills, but may not possess the skills or disposition to think critically about engineering problem construction and framing, power relations, and other social dimensions shaping engineering practice. However, recent findings of Ford et al. (2021), Lutz and Paretti (2021), and Gewirtz and Paretti (2021) suggest that recent graduates do not face a critical thinking "skills gap," but a "context gap" upon entry to the workplace due to the situatedness of engineering work and communication practices. While it may not be possible within the undergraduate education context to fully replicate the contexts graduates will face in practice, our goal is to interrogate how a focus on engineering judgment enacted through writing processes may permit an expanded role for the critical perspectives advocated by Claris and Riley (2012). Our method combines reflective conversation with reflexive thematic analysis to obtain three themes: "How do the solutions we come up with interface with society?" [the socio-technical aspect]; "A lot of the previous EMSE stuff has been very *technical* technical" [previous work emphasizes technical elements]; and "…this really nice pre-design senior capstone project where we have a lot of intellectual freedom" [pre-senior design]. We hope the implications of teaching critical thinking in engineering judgment presented in this paper will spark the integration of critical thinking into other engineering curricula.

Introduction

Critical thinking is central to engineering education, yet it does not have a single agreed operational definition in engineering education. One useful definition described by Ahern et al (2019) quoting Facione (1990) is: "[critical thinking] is a '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 judgment is based.'" Although this definition reflects common ideas shared by many investigators, critical thinking as understood by engineering educators has been defined more narrowly. Critical thinking in engineering is more likely associated with successful application of specific types of reasoning and validity standards (citation), while also incorporating some consideration of affective dispositions. Engineering educators, compared with other fields according to Ahern et al. (2019), often have a less rigorous definition of critical thinking and its supporting theories, making it difficult to investigate interventions that can improve engineering critical thinking.

Objective

In this paper, our objective is to describe our mutual engagement with a writing assignment for 3rd year undergraduate systems engineering students intended to foreground engineering judgment and critical thinking in student writing processes from the perspective of an instructor and an undergraduate student. The course in which our work is situated is the Spring 2023 Semester offering of EMSE 3855W—Critical Infrastructure Systems offered in the Department of Engineering Management and Systems Engineering (EMSE) at George Washington University. The main objectives of the course will be summarized in the Methods and Approach to Research section of this paper. Our method of inquiry is an exploratory autoethnography **to construct key elements of the ways both student and instructor participate in the construction of engineering judgments through the course's writing processes**. Our work reflects the observations of an undergraduate learning assistant (Patel) that attended each class session during the semester the student co-author (Ferguson) was enrolled by the course. The course was taught by the lead author (Francis). The principal analyzed in this reflective essay were obtained from a 30-minute reflective conversation between Francis and Ferguson that we analyzed using reflexive thematic analysis (Braun & Clarke, 2021). We hope that our reflective essay advances the possibility for engineering judgments constructed in well-designed writing assignments to improve critical thinking capabilities.

Background and Literature Review

Improving critical thinking, is considered an urgent need because engineering graduates are often considered deficient in these skills upon entry to the workplace. Claris and Riley (2012) discuss this "situation normal" where engineers often possess strong logical thinking skills, but may not possess the skills or disposition to think critically about engineering problem construction and framing, power relations, and other social dimensions shaping engineering practice. However, recent findings of Ford et al. (2021), Lutz and Paretti (2021), and Gewirtz and Paretti (2021) suggest that recent graduates do not face a critical thinking "skills gap," but a "context gap" upon entry to the workplace due to the situatedness of engineering work and communication practices. While it may not be possible within the undergraduate education context to fully replicate the contexts graduates will face in practice, courses designed with a focus on engineering judgment and critical thinking as enacted through writing processes may adequately simulate aspects of engineering work contexts in ways that require students to strengthen their critical thinking skills. Furthermore, the literature suggests that unstructured, team-based projects with extensive communication requirements such as a written report, oral presentation, or proposal may permit greater student engagement with the critical perspectives advocated by Claris and Riley (2012).

What is critical thinking?

According to Claris and Riley (2012), there are six themes prevailing in the critical thinking literature in engineering education:

- The <u>skills and dispositions</u> perspective. In this perspective, critical thinking is a combination of cognitive skills and affective dispositions. Some researchers suggest that a critical worldview must underly either context or skills. This perspective indicates that students should develop a critical, questioning state of mind, although this questioning does not extend to questioning the foundational assumptions and power relations within engineering (e.g., logical positivism, cost-effectiveness, scientific principles, etc…).
- The <u>reason and validity</u> perspective. This perspective equates critical thinking with evaluating arguments based on standards of logic and reason to assess validity judgments. This perspective is supported by logical positivist epistemology. Some proponents of this perspective equate critical thinking to the process of analyzing, synthesizing, or evaluating information or communications

as a guide to belief and action. Moreover, this perspective also involves an evaluation of the sources of information, including observations, reflections, experience, or reasoning.

- The questioning perspective. This perspective involves the use of Socratic teaching or questioning methods to promote active learning and criticality.
- The meta-cognition and reflection perspective. This perspective equates critical thinking with reflective thinking oriented towards action. It is a reflexive critique of the structure or orientation of the reasoning process.
- The reflective judgment perspective. This perspective adopts the King and Kitchener (2004) reflective judgment model. In this perspective, judgment is the willingness to critique one's own reasoning. Reflective thinking addresses real-world problems requiring reflection and judgment in the face of uncertainties. In addition, this perspective requires attention to epistemic assumptions, requiring students to become aware that knowledge is constructed. However, critical thinking in this perspective is limited to logical thinking skills and formally structured problem-solving processes.
- The creative thinking perspective. This perspective involves generating possibilities, conceptual formulation, development of alternatives, comparison and choice, design, and problem solving. These processes are combined with recognition, perception, and interpretation of contextual clues, values, and feelings. This perspective embraces ambiguity and change.

These critical thinking perspectives embrace a range of theoretical frameworks, including critical theory, boundary spanning, structure-agency, figured worlds, critical (liberatory) pedagogy, and reflective judgment. This diversity of perspectives and theoretical frameworks makes it challenging to unequivocally adopt a well-defined notion of critical thinking. Moreover, it can be difficult to introduce students to the philosophical assumptions that must be evaluated before committing to any of these critical thinking approaches (i.e., epistemological, hermeneutic, or ontological assumptions). As a result, Ahern (2012) argues that engineering educators rely on an intuitive understanding of what critical thinking is in their disciplines. More importantly, engineering educators often use critical thinking and engineering judgment interchangeably to describe what is meant by critical thinking in engineering (Davis, 1998; Davis, 2011).

What is engineering judgment?

Engineering judgment is challenging to unequivocally define. Suppose we start off with the term "judgment". Judgment is widely discussed in philosophical and economics literature. In those fields, judgment is commonly defined in terms of the cognitive processes of perception, choice, feedback, and control (Gonzalez, 2017). How does this relate to engineering judgment and critical thinking? Some writers argue that engineering thinking is engineering judgment (Davis, 1998). Francis et al. (Francis et al., 2021a; Francis et al., 2021b) observe that engineering judgment is often defined as a quasi-rational combination of analysis and intuition can be extended to professional practice by considering: i.) the ways practicing engineers interact with computational tools and techniques that facilitate their work; and, ii.) considering how traditional professional judgments can be reified in common design practices such as standards, safety factors, or policies and regulations. In later work, Francis et al. ((2022), p.81) emphasized the inter-professional aspect of judgment processes in teams and extended their work to define engineering judgment as a holistic participatory capacity integrating the technical and social context of engineering work, the cultural and discursive production of professional identities, and naturalistic decision-making processes. Moreover, the ambiguity and uncertainty that is often present in design or analytical situations requires interactions among professionals working in teams such that judgment "emerges" as the interaction of internal (belonging to the subject alone) and participatory (the result of interactive communication practices) judgment processes play out.

Implications for Educators

The prior section describes what critical thinking and engineering judgment are. When considering how to strengthen engineering judgment and critical thinking through assignments intended to reinforce engineering judgment capacities, the gaps identified by Claris and Riley (2012, p.110) imply four suggestions for improving the ways critical thinking is adopted in engineering pedagogy:

1. Engineering education should provide opportunities for students to "analyze the co-construction of power and knowledge in engineering";
2. Engineering education should help students to "develop an epistemic awareness that includes a critique of the scientific method and positivist epistemology";
3. Engineering education should engage students in a "creative practice that is both reflective and reflexive"; and,
4. Engineering education should be "grounded in praxis oriented towards social justice."

The course and assignment that provide the context for this essay directly address suggestions 1-3, and indirectly address suggestion 4.

Context: EMSE 3855W—Critical Infrastructure Systems

The lead author (Francis) teaches a course at his institution called Critical Infrastructure Systems. This course is a writing in the disciplines/writing across the curriculum (WID/WAC) style course that is required for all graduates from his institution's systems engineering undergraduate program. Roughly, the overall objective of this course is to engage students in policy-relevant analysis related to critical infrastructure systems. The analytical tools studied in the course include: risk analysis, uncertainty analysis, benefit-cost analysis, and multi-criteria decision analysis. The principal learning objectives of the course are:

- To decompose the design or operational objectives of an infrastructure system into fundamental objectives that can guide relevant decision-making processes.
- To formulate and evaluate infrastructure system projects of the students' choice that can be evaluated using quantifiable and/or measurable attributes. Students may choose to formulate and evaluate policies, standards, infrastructure system components, projects with which they have had past or other experience, small-scale integrated infrastructure systems (such as low-impact development projects), or small-scale interdependent networked infrastructure systems (such as campus-wide roadway networks).
- To use benefit-cost analysis or multi-criteria decision analysis to justify infrastructure system actions and/or recommendations.
- To explore the robustness of the proposed action(s) or recommendation(s) to uncertainties in the decision context using sensitivity analysis.

The students in the course work in small teams—1-4 students in each team depending on enrollment—and the culminating assignment in the course is completion of a semester-long writing project documenting the team's exploration of the infrastructure system problem and analysis they have formulated. The writing project is, generally, the technical report genre, although occasionally students have written white papers or proposals. The topic of the analysis is not specified in advance, but is left to the discretion of the student teams; however, the topic be directed towards fulfillment of a critical infrastructure need. Finally, the students are provided with a very limited set of requirements. While students are not required to use specific mathematical or physical theories to model their systems, they are required to build models that would enable their decisions to be explored using sensitivity analysis. Furthermore, their decisions must incorporate multiple criteria.

Method and Assumptions

Research Orientation and Worldview

This work is inspired by a transformative worldview (Charmaz, 2014; Creswell & Plano Clark, 2017) that is informed by my (Francis's) interpretations of conscientizão (Freire, 2000) and consciencism (Nkrumah, 1964). The transformative worldview asserts that people must be awakened to the realities around them to then act on this reality as intelligent subjects. As Charmaz (2014) writes, it is "situated in conceptions of justice and injustice". In conscientizão, Friere emphasizes reflection, involvement, and action. In his writing, anything less than co-participation in this type of reflective action dehumanizes people and proscribes their liberation. Similarly, Nkrumah articulates a philosophy of intellectual revolution in which one's thinking or philosophy is directed towards the redemption of society. He wrote with the goal of presenting a philosophical worldview that would enable African societies to assimilate Western, Islamic, and Euro-Christian elements into the African context. Again, the goal was a reflective transformation of society. I (Francis) adopt this orientation in my teaching and research, which I will call by the English transliteration of Friere's term, conscientization. I aim to introduce students to the concepts and sciences related to infrastructure systems in ways that prepare them to participate in reflective action that will make these systems more sustainable, reliant, resilient, and community-empowering.

Theoretical Framework

This work adopts the constructivist theoretical framework. Corbin and Strauss (2008) describe the constructivist framework as one where researchers construct concepts and theories from accounts that are constructed by participants from their own experiences. Creswell and Plano Clark (2017) note that this will imply research being shaped "from the bottom up" via participants' individual perspectives and experiences. As these perspectives and experiences are analyzed and evaluated by researchers, these individual experiences yield to broad patterns and understandings. Consequently, Creswell and Plano Clark's view of the constructivist framework is focused on understanding through the observation of participants' meanings for the purpose of exploratory theme generation.

Researcher Positionality

Royce Francis is an African-American male systems engineering associate professor with backgrounds in environmental engineering and risk analysis. Royce is motivated to pursue engineering education research as a result of prior semesters' teaching experiences in one of the required courses he teaches, EMSE 3855W—Critical Infrastructure Systems. This course is one of his department's Writing in the Disciplines (WID) requirements, and classroom discussions made him curious as to whether the students' perceptions of and engagement with some of the material in the course might be related to their identification with the engineering profession more broadly. Additionally, his experiences in the NSF Research Initiation in Engineering Formation program have made him driven to learn more about the interlinkage between the emergence of professional identity and professional judgment capacity pre-college, where much of the foundation for students' professional identity and undergraduate persistence is laid. These interests and classroom experiences inform his understanding of both the literature on engineering judgment and critical thinking and his understanding of his students' experiences in EMSE 3855W.

James Ferguson is a mixed, Asian-American-Caucasian male systems engineering undergraduate student with backgrounds in operations research and economics. James is motivated to pursue engineering education research because of several semesters' experience as a teaching assistant in varying courses including EMSE 3855W—Critical Infrastructure Systems. He is curious about the intersection of technology and human behavior and sees EMSE 3855W as a strong course model for sparking discourse on critical thinking in engineering both as a past student of the course and current member of the teaching team. His experience as a participant in Lockheed Martin's 2023 Ethics in Engineering competition has driven him to learn more about the role of critical thinking in engineering judgment and how to integrate critical thinking in engineering curricula.

Throughout the remainder of the manuscript, we use first-person pronouns (I/we), and first names to refer to each other, as appropriate. In qualitative analysis, the positionality of the researcher(s) means that both the perception and interpretation of data require subjective construction. We are active participants in both the observing and revealing of the data analyzed in this paper. Thus, to allow the reader to sense this closeness to the data, we depart from the third-person ideal traditionally used in scientific writing.

Data Collection.

The data collection and analysis approach for this paper are summarized in Figure 1.

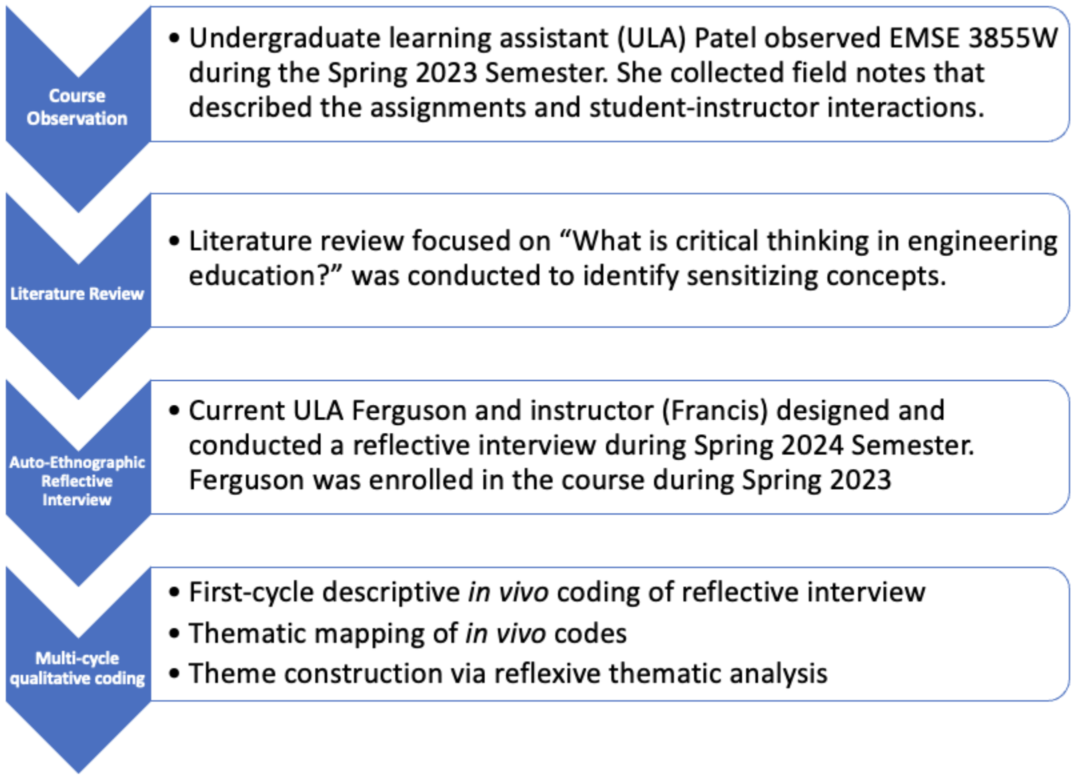

Figure 1. Overview of our data collection and analysis method.

The data analyzed for this paper are derived from direct observation and reflection and two primary sources: (i) a prior undergraduate LA's (Kaveena Patel) notes and observations collected during her attendance at each class session in the Spring 2023 semester; and, (ii) a reflective conversation (Feldman, 1999) held between Royce and James. This reflective conversation methodology, loosely related to the collaborative conversation method of Feldman (1999), was centered around how the critical infrastructure systems final project influenced the way that James and his peers practiced critical thinking in the course and how he felt that the course shaped his and his peers' critical thinking practice after the course. The reflective conversation also explored how his experience in the course may have influenced his view of the things he did or learned throughout his systems engineering education. James and Royce discussed the goals for the conversation in advance, and developed a semi-structured interview protocol based on seven guiding questions. The reflective conversation was scheduled for a 30-minute Zoom call to make a high-quality recording easier to obtain. The questions guiding the conversation were as follows:

1. What do you remember about the main project assignment in this class?
2. In what ways was this assignment different from assignments in other courses (restricted to EMSE-only? SEAS-only?)?
3. What are the ways in which you exercised creativity in this course?

4. How did you participate in problem formulation and framing?
5. What did you do in this project beyond just applying previously taught theories?
6. How did you explore ambiguity or uncertainty in this project?
7. How did this course influence the way you think critically about engineering problems?

The conversation was led by Royce due to his prior experience with semi-structured interviews, and resembled a semi-structured interview, but also involved Royce's own exploration of his goals for the course during their conversation. At times Royce also provided his own reflective comments on James's observations. The conversation was conducted virtually, and recorded via Zoom. An "intelligent verbatim" transcript of the conversation was produced using MacWhisper software and checked against the audio recording. This transcript was then prepared for manual coding and analysis in Microsoft Word.

Data Analysis

The data were analyzed using reflexive thematic analysis. According to Braun and Clarke (2021), reflexive thematic analysis is "a method for identifying, analyzing, and reporting themes within data." Reflexive thematic analysis is flexible and can be adapted to a range of theoretical frameworks and can facilitate development of a detailed, complex account of the dataset. The data were coded and themed by Royce, and both Royce and James reviewed the final themes. The first step in the process involved obtaining an intelligent verbatim transcript of the reflective conversation and checking the accuracy of the transcript against the audio files. Coding and theme identification involved a three-step process: *in-vivo* coding, thematic mapping, and theme construction. First, the interview was coded using an *in vivo* approach. Royce would identify phrases or key words in the original data that represented the main idea or thought of the paragraph or sentence. He chose an *in vivo* approach in favor of a preliminary codebook to utilize an emergent coding method that prioritized James's voice. The *in vivo* coding was completed in Microsoft Word, and the list of *in vivo* codes was extracted manually. After the *in vivo* coding of the interview was completed, Royce manually constructed a thematic map from the *in vivo* codes. The thematic mapping facilitated a deep familiarity with the inter-weaving narratives James expressed during the reflective conversation that helped to construct inter-relationships among the various *in vivo* codes created during the first step. This thematic map was then utilized to construct the three themes reported in the next section.

Analysis

Three themes were constructed from the transcript of our conversation: "How do the solutions we come up with interface with society?" [the socio-technical aspect]; "A lot of the previous EMSE stuff has been very *technical* technical" [previous work emphasizes technical elements]; and "…this really nice pre-design senior capstone project where we have a lot of intellectual freedom" [pre-senior design]. These three themes help us to construct the ways that James and I participated in the practice of critical thinking throughout the Critical Infrastructure Systems Course. Although this analysis prioritizes James's voice, neither of us can understand or experience critical thinking in this context apart from our mutual interactions with each other, the other students and learning assistant in the course, and the broader institutional context. As a result, the reader should imagine me in the background, trying to adapt and revise the course to emphasize the aspects of critical thinking that James and other students describe, while intentionally trying to highlight features of this course that distinguish it from their prior experiences in the systems engineering department.

Theme 1: "How do the solutions we come up with interface with society?" [the socio-technical aspect]

An important aspect of how James described his participation in critical thinking in our course was through exploration of the ways that social factors influence knowledge claims in engineering. This was one of the primary dimensions of the impacts of this course on his broader thinking, and was one of the primary distinguishing factors of this course relative to his other courses in Systems Engineering and beyond at GW. For example, when asked to describe what he remembered about the course, James responded:

> *And I think a second part of that that really interested me -- particularly, especially with what my group did -- was the socio-technical aspect. It felt like a lot of what we had analyzed and studied in semesters prior were very technical systems where it felt like to an extent it was pretty black and white and that there are right solutions and there are wrong solutions…*

We'll come back to the second half of the quotation later in the analysis. The socio-technical aspect was a clear marker of the type of thinking that he and his peers engaged in in the course. The term "socio-technical systems" could be credited to Thomas Hughes (2021), and has found increasing application in contemporary engineering discourse. Although many people are using the term, it is not well-defined in undergraduate engineering courses. More importantly, undergraduate engineering students often do not experience courses that intentionally and systematically intersect the social and the technical in the ways described by Hughes. We see this as James continues:

> *…not a whole lot of thinking about, well, how do the solutions we come up with interface with society. And... how is the work that we do, how does that end up affecting all the different kinds of stakeholders, and how do we effectively identify all the stakeholders within a given company?*

As he explains, his experience with his prior courses have not provided as much of an opportunity to explore how the solutions we come up with as engineers interface with society. Yet, this is precisely what is meant by Hughes (2021), Nye (2006), Leveson (2016), and many other theorists when they use the term socio-technical systems.

What James is describing implicitly, if not explicitly, is the way that conceptualizing engineering solutions in terms of socio-technical systems ideas requires one to adopt a critical perspective towards the types of knowledge claims that must be made in engineering work, and how they are justified. In fact, the socio-technical systems idea is a compromise between a deterministic, techno-centric understanding of how technology shapes society and a critical re-orientation of these frameworks towards the social construction of technology (Hughes, 2021). The socio-technical systems aspect of the course, as experienced by the student, requires the participants in the course to move reflexively between the ways technical artifacts or systems shape social systems and social systems are designed to shape and control technical artifacts or systems (Leveson, 2016). These reflexive moves involve the student's critical evaluation of what prevailing assumptions or theoretical orientations will guide their work. Again, this does not happen consciously, as many students have not been exposed to the discourses that would enable them to articulate these moves. However, we see James describing this critical work in his own experience:

> *…sitting through and watching the projects that my peers were working on that seemed to be a common theme no matter what people were working on. Where a lot of those questions were either at their core societal questions or had some kind of component where it was, "Well how does human behavior affect the way we analyze the system?"*

It goes without saying that much of the undergraduate intellectual experience requires students to set aside both systems thinking and interaction with human behavior in order for students to become fluent in certain aspects of scientific or mathematical discourses utilized in engineering practice. However, because engineering involves action (Arendt, 1959) in society, questions of systems and human behavior engage students in decomposing and synthesizing core societal questions that bear on what their work can do or should be doing. These core societal questions, in turn, inform the ways students interrogate their own work:

> *… just because there are end policies that work, that resolve your problem statement, it doesn't mean that all of those policies are good enough to be implemented…*

And;

And there is so much randomness and uncertainty along the system and amongst, you know, just generally human behavior and decision making that there has to be a lot of thought put into, well, how are people going to bring it? And is this policy actually going to be effective among a group of people? And so I think that's something that I have really thought about more, especially in senior design now, is thinking about that aspect and not just saying, well, have the metrics improved? Does the tool work? Like we're developing a decision support tool. Is it something that is actually going to be used in the case that it could be helpful? Are decision makers going to be willing to use it? Because if not, then there's really no point in continuing the work.

James's reflections on how he participated in critical thinking through engagement with the socio-technical aspect of the course that forced him to wrestle with core societal questions contrasts with his understanding of his other engineering coursework as described in Theme 2.

Theme 2: "A lot of the previous EMSE stuff has been very technical technical" [previous work emphasizes technical elements]

Another area of critical thinking practice encountered by James in his Critical Infrastructure Systems course experience is engaging in metacognitive reflection about what was done in prior courses and how those experiences transferred to this course. In reflecting on the differences between Critical Infrastructure Systems and his prior systems engineering courses, he notes:

I think this is interesting and this is going to push right back into the whole socio-technical thing because I think a lot of, like I said before, a lot of the previous EMSE stuff has been very technical technical.

From this, we can see how this theme builds on the socio-technical aspect noted above by contrasting his awareness of the centrality of socio-technical factors in systems engineering against the foregrounding of the "technical" focus of most of his prior engineering courses. His prior courses underexplored human behavior and social factors' shaping of the design, operation, and maintenance of engineered systems. More than this, however, this technical aspect was reflected in some of the ways that systems knowledge and thinking was perceived. For example:

Of course, our analysis in dealing with a lot of uncertainty and just kind of doing the best we could to estimate certain values and opinions of different stakeholders, attributes to trying to understand some of the uncertainty among the process and how you can interact with what naturally exists in that world.

This idea that there are engineered systems elements that "naturally exist" may reflect the persistent idea that there are some things which can be demonstrated objectively, some things that can be constructed subjectively, and that there is limited overlap across these things. Those things that "naturally exist" may be those things that can be demonstrated objectively. This is one sense in which the term "naturally" can be understood in this context, which may explain why James's observation of the socio-technical emphasis in the Critical Infrastructure Course is so prominent. At the same time, James's observation indicates a use of the term "naturally" to reflect that which exists in the "real world" outside of the academic classroom. In this sense, "naturally" reflects his awareness of the need to develop the critical thinking skills required to explore the ways the things he and his peers have learned in their prior courses can be used to represent and analyze real-world systems that can be empirically observed.

James's observations explore this more concretely when he compares the nature of his analysis in this course with the nature of his analysis in prior courses. First, he asserts the novelty of these types of thinking processes:

And the sensitivity analysis, because particularly for our project, we had really no hard data and we didn't have enough time in the course to actually get real data to work with. So that really forced a lot of creativity in trying to draw conclusions from something that at face value appeared to be very ambiguous, especially because we had never really dealt with a problem that looked like that before. Every problem we dealt with in the past was all textbook problems that had all the information you needed to complete an analysis and make a decision. But lacking that, we really had to start pulling out things and thinking back *from course to course about, well, how can we use the tools and techniques we've learned to elicit some sort of insight in a realm that we don't have a whole lot of knowledge of right now.*

It is common in the critical thinking, problem-based learning, and meta-cognition literature in engineering education to observe the challenges students face when they are confronted with problems characterized by ambiguity and incomplete information. Despite the regularity that this is reported in the literature, James's account reflects the relative lack of frequency with which he's faced these types of problems. Most of his assignments, in his recollection, have plenty of requirements against which to measure his efforts, whereas this course had relatively few upfront requirements about what systems to analyze and how to analyze them:

You know, it's something that you're very well known for among students in the department that a lot of your assignments have very few requirements to them and that gives you a lot of freedom to really choose what you do. And on one hand, it is very daunting, but at the same time, you know, it really lends itself to that creative lens of really thinking critically about what you want to do.

He also observed that much of the work in his prior courses involved "black and white" or "correct" solutions, whereas in this course he observed that engineering problems that he might face in the future are not "black and white" and may not have unique correct solutions:

It was a huge reminder that engineering problems aren't black and white.

His observations can be summarized in one final quotation:

And I think that's a really big takeaway from this is just, you know, being reminded that it's not -- like solving these kinds of problems and doing this level of systems analysis is not just solving a set of differential equations. You know, that's not going to get you the answer.

This reflects the fact that he has become more aware that engineering requires more than familiarity with mathematical, chemical, or physical techniques. There is a type of analytical thinking that employs these skills in ways that can "get you the answer". While James is one student, his observations that "*technical* technical" thinking is not enough to solve challenging problems relevant to real-world experiences has been anecdotally shared by many students that have given me informal feedback about this course. This leads to Theme 3.

Theme 3: "…this really nice pre-senior design capstone project where we have a lot of intellectual freedom" [pre-senior design]

Theme 3 is our culmination of the overall impact of this course in our students' experiences in systems engineering at GW. Many students reflect the sentiment that this course is a type of capstone course that helps to prepare them for the type of thinking involved in constructing and implementing their systems engineering senior design projects:

I think I remember it kind of being, like I said in the past, this really nice pre-senior design research semi-capstone like project where we have a lot of intellectual freedom

This notion is highlighted by the sense of intellectual freedom the students sense. This intellectual freedom requires creativity that engages their critical thinking faculties along several dimensions: navigating ambiguity and dealing with uncertainty; exploring how technological systems interact with other systems; defining the boundaries of one's own system and identifying the scope of their analysis; doing the model building and analysis; and making decisions. It is clear that James views his prior experience in the Critical Infrastructure Systems course as a low-stakes opportunity to develop these dimensions of his critical thinking faculties before they are employed in his senior design project year.

The first component of this process requires James to "explore how this stuff works":

For my group as a whole, we still have that sense where the big stories you knew about, you knew about Sam Bankman-Fried in the fall of FTX, you knew what Bitcoin was, you knew what Ethereum was, but

> *outside of that, you might not have known that much. And so I think there was a lot of exploring just how does this stuff work, which I think is good. And I think we've started to get more into that.*

This practice combines the prior two themes—merging his technical preparation with a deeper understanding of the socio-technical aspects of his system focus—with an unfolding awareness of the complexity of the domain he chose for the project.

> *And I think a lot now where an interesting parallel to our project in this current time would be studying Gen A where everyone's heard of ChatGPT and everyone's used it a little bit, but how many people actually know what's going on beneath the surface and what the real level of interconnectedness is, all of the different infrastructure sectors that get tied in?*

His awareness of his project topic—the need for regulations of Bitcoin and Blockchain-based cryptocurrency trading—was prompted by exposure in popular press and literature. At the same time, their development of the mapping of the various technical and regulatory systems involved in this topic made him realize not only the complexity of the domain but also the fact that most of the resources he and his team were able to identify remained at a superficial level.

As a result, their team was confronted with a lot of uncertainty and ambiguity that needed to be resolved in order to formulate an actionable problem.

> *So I think that was a big part for us was we started with this initial understanding that we're working within the financial sector, but there was also a question of, "well, how does this kind of technology interact with things that remain outside of the financial sector?" And I think that was a big thing that we looked into and trying to just be able to really identify what are the bounds of the system and where do they exist? So I think that when we talk about the systems level analysis, to me, that's the first major step, right, is defining what your system is. And I feel like that's what a lot of our project was.*

This is one of the most important places that a critical awareness of the assumptions involved in engineering work can be brought to bear on the trajectory and outcomes of engineering work processes. Resolving the ambiguity requires James and his peers to compare what they think is most important from the domain against their sense of professional ethics and judgment—"What should the objectives of their analysis be and how should they be justified?" The choices James and his peers made at that step would impact the choices they make in system definition:

> *So I think that when we talk about the systems level analysis, to me, that's the first major step, right, is defining what your system is. And I feel like that's what a lot of our project was. Of course, our analysis in dealing with a lot of uncertainty and just kind of doing the best we could to estimate certain values and opinions of different stakeholders*

And

> *I think especially the way that this course fits into that junior spring semester where you're really in the meat of starting to get a full understanding of "what does a major in EMSE mean?" and "what do you want to do with it?" puts it in a great spot where your gears are starting to turn about where you want to start your career trajectory and you're able to, if you want, like my group did, which was tailoring our project towards those interests. So I think that was a major avenue for creativity. I think the second part that was also big, especially for us, was when it came to doing the analysis and doing the model building and the MCDA…*

While "defining what your system is" and "doing the analysis and doing the model building", on their face, are the areas that most people think of when they consider what it means to be an engineer and exercise engineering judgment (Baybutt, 2018), many undergraduate students rarely have the opportunity to practice these skills in their coursework. On the one hand, I believe that engagement in design-based out-of-classroom activities or organizations has a strong potential to improve persistence in engineering majors, perhaps we as undergraduate engineering educators are missing an opportunity to spread these skills throughout the curriculum. For example, Gainsburg's (Gainsburg, 2006, 2007, 2013) study of structural engineering students and professionals revealed that while both students and professional engineers faced situations where they were required to make mathematical judgments to construct mathematical models that support action, they did not often remember being taught these skills. Two efforts that I am personally familiar with intended to do this at the undergraduate level are the KEEN Entrepreneurial Mindset (KEEN, 2024) and the Lemelson/New Venture Fund's Engineering for One Planet Framework (Engineering for One Planet [EOP], 2022). As educators adopt these frameworks, students will be faced more frequently with unstructured problems characterized by ambiguity and incomplete information that will require judgment and critical thinking.

Perhaps one of the final takeaways we should leave you with in Theme 3 involves personal and professional development more so than the development of specific skills:

> *I think one of kind of like the big things that we accomplished with this project, which wasn't necessarily like a project. This is something that I saw really a lot, especially in my personal growth was in an academic environment and being comfortable with being uncomfortable. I think with the level of ambiguity and uncertainty we had at the very beginning of the project, it's very daunting as you're trying to develop your problem statement, develop what are the modeling tools you're going to use? How are you going to analyze this? How are you going to measure sensitivity? All of these things when you don't have a clear definition of the system you're analyzing, which is a very real problem to have, especially I think in academia, where a lot of the stuff is the goal is to further research on things that have not had full research done already and you don't know it. And I think especially, it's something that has come up again in senior design. It's come up again in a couple of other classes where we've been given the freedoms or really develop our own problem statements and told, just go out and find stuff to support your claims and your analysis and drop [unintelligible] from there. And so I think, especially from that lens, it's just getting comfortable with getting uncomfortable.*

As educators, we must remember that there is a transition between learning the discipline-specific discourses of engineering (i.e., mathematical and technical skills) and acquiring the professional skills and practices (i.e., ethical awareness, judgment, and communication skills) required to operationalize their technical skills. In many situations, these skills are taught separately; however, in practice, they are inseparable. The technical skills are enacted through rhetorical practices (Weedon, 2019) that reflect the needs and expectations of professionals mutually interacting in recurrent situations (Miller, 1984). Students must practice and receive feedback on their ability to engage in these situations (Berkenkotter et al., 1988), and their first experiences with this transition will be very uncomfortable for most.

Conclusion

The teaching of critical thinking in engineering judgment is critical to decrease the "context gap" undergraduate engineers face on entry into the workplace. The writing assignment presented in this paper and discussed in our interview explores how to teach critical thinking in engineering judgment through the student writing process. Though impossible to fully replicate the contexts of the professional engineering environment, this assignment serves as an example of how to enable critical thinking through a semester-long research project. As technological innovation accelerates, the need for engineers to think critically about engineering problem construction and framing, power relations, and other social dimensions shaping engineering practice will increase. We hope the implications of teaching critical thinking in engineering judgment presented in this paper will spark the integration of critical thinking into other engineering curricula.

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