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WIP: Using Challenge Essential Questions to Connect Technical, Social, and Ethical Content in a First-Year Engineering Program

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Work in Progress: Using Challenge Essential Questions to Connect Technical, Social, and Ethical Content in a First-Year Engineering Program

Abstract
This Work-In-Progress paper will describe a specific intervention to help first-year engineering (FYE) students make connections between technical and sociotechnical content. Foundational engineering courses are designed to introduce new undergraduates to the discipline of engineering and help them develop the skills and knowledge to succeed throughout their studies. Students are introduced to technical content (e.g., CAD, programming, fabrication, the design process) as well as sociotechnical content (e.g., STS frameworks, engineering ethics, sustainability, professional development, teamwork, and communication). These two knowledge bases serve students best when clearly connected, yet students often struggle to establish that connection for themselves, and instructors' attempts to emphasize their interrelated nature are not always successful. To that end, this work-in-progress paper outlines the implementation of a set of sociotechnical "Challenge Essential Questions" (CEQs) in a two-semester first-year engineering course at the University of Virginia (UVA). CEQs are designed to weave together the technical and social aspects of engineering design. As students learn sociotechnical frameworks to inform their design decisions and processes, they can assess multiple aspects of engineering challenges beyond just the technical and quantitative. While these questions were developed for the content of UVA's FYE program, they could be adapted to the needs of other institutions.

Introduction and Background
In recent years, sociotechnical knowledge has become an increasingly prominent area of study in the engineering education community [1], [2]. Twenty years ago, the National Academy of Engineers [3] laid out a plan for what the "Engineer of 2020" would be defined by: leadership in moving the world forward in an ethical, sustainable manner. However, as a more recent survey demonstrated, ethical and sociotechnical considerations have remained an undervalued part of students' perceptions of professional engineering work, particularly among male students [4]. As a result, further investigation is needed to understand how and why these attitudinal and knowledge shortcomings persist, and further work to address them is needed. This WIP paper introduces an intervention to weave sociotechnical thinking throughout the first-year engineering (FYE) course at one university. A set of "Challenge Essential Questions" (CEQs) were developed around core sociotechnical concepts and skills. The CEQs, listed in full below, address the following topics: sustainability, problem definition, Universal Design, engineering ethics, teamwork, and communication.

1. How are you addressing economic, societal, and/or environmental sustainability challenges in the design process and any potential tradeoffs?
2. Problem framework: Who are the primary technical, social, natural, conceptual, and economic actors and how do they affect your process?
3. How are you incorporating the principles of Universal Design through the process?
4. What are the ethical considerations and implications that you will (or did) consider when generating a solution?

5. How do you work effectively as a team member, and what tools do you use to help your team be productive?
6. How are you planning to effectively document and communicate the merits of your design and process to relevant stakeholders?

These CEQs are then used to prompt reflection and integration of sociotechnical perspectives into every step of the design work students engage in, which requires students to keep the broader impacts of their work in mind both in the course and beyond the classroom in professional practice. To properly understand the development and implementation of the CEQs, background on the course will first be provided.

Course History

In 2019, administrators at a large public mid-Atlantic university began a study of their FYE program to evaluate whether it was providing students with the skills and knowledge that would be most useful to them in their professional careers. To do so, a survey was sent to engineering faculty, university alumni, and employers who had hired university graduates in the past. This survey asked participants to rate the importance of a variety of technical and sociotechnical skills and knowledge sets, ranging from vector calculus and introductory programming to conflict management and ethical considerations. In combination with a connected evaluation of the current FYE curriculum and structure, the results of the survey identified a distinct separation between technical and sociotechnical skills in students' minds, and a preference for the former amongst many. These findings set in motion a broad restructuring of the FYE program with a focus on interweaving technical and sociotechnical content to keep them aligned for students. These efforts were supported throughout by the university's Science, Technology, and Society (STS) faculty, who provided insight, content, and guidance into how best to integrate sociotechnical content into the course. The resulting CEQs are part of these restructuring efforts. For further information about the task force and restructuring efforts, see Laugelli et al. [5].

Course Structure

The current FYE program is a two-semester sequence, built to provide a foundation in a range of technical and sociotechnical skills and concepts, that all engineering students must complete to begin their major-specific coursework in full. The first semester, which is the focus of this paper, is divided into three distinct modules, each with their own associated project. Module one focuses on a short and simple iteration-driven project requiring students to develop and test a design and collect data. This is paired with the introduction of Actor Network Theory (ANT), a sociotechnical framework that emphasizes the interconnectedness of a variety of different human and non-human elements, or actors, in any given project or system, and provides students with a framework to further understand the posed problem. Module two is very technically focused, tasking students with developing a microcontroller system, 3D modelling components for their system, and combining elements into an interactive display. In the most recent iteration of the course, there was no new sociotechnical content introduced during module two, though ANT is revisited in the new context. However, teamwork and communication skills and techniques are emphasized. The final module, module three, is sustainability focused, with student teams identifying a problem local to their campus, prototyping solutions, and testing the feasibility of their designs for their intended context. The third module features introductions of a three-pillar model of sustainability (environmental, economic, equity), the principles of Universal Design (UD), and character-based professional ethics.

There are seven instructors at the study institution, all of whom teach both Fall and Spring semester courses in sequence. There is a shared syllabus and course plan, though individual instructors retain freedom to plan their lectures and activities in the way that best suits them. That is to say, all instructors cover the same general content in a similar order and timeline, but specific examples, anecdotes, and activities may vary. Each instructor teaches three sections with a maximum of forty students per section. In total, approximately 720 students take the courses each year. The courses are taught in lab spaces, facilitating both lectures and design work in the same location. This study will focus on the first course in the sequence, as it was the pilot implementation of the CEQ intervention described later on.

Literature Review

The CEQs developed for use in the first-year engineering curriculum resonate with the framework of experiential Challenge Based Learning developed by Apple Inc. and productively incorporated into classroom learning experiences by engineering faculty in various undergraduate programs. However, our CEQs differ in that they are primarily a tool for reflection and analysis instead of project ideation. By considering the CEQs in conjunction with each design project in the first semester, students progressively develop proficiency in integrating insights from the fields of STS and engineering ethics into their approaches to engineering design challenges.

Apple's Challenge Based Learning framework, which developed from the Apple Classrooms of Tomorrow – Today project launched in 2008 [6], provides an experiential, problem-based model of learning in which students work collaboratively to identify an actionable research question ("essential question") that governs their work to develop and test solutions to real-world problems they care about for an authentic audience [7]. The "essential question" development occurs in the first phase of the framework, called "engage." In the "engage" phase, students begin by generating "big ideas" related to themes important to them and their learning community, such as democracy or sustainability [8]. From there, they turn these "big ideas" into a series of questions that ultimately yield a single actionable "essential question," which guides their research (phase 2: investigate) and iterative development of solutions (phase 3: act) (source 3). In Apple's Challenge Based Learning framework, then, the "essential question" is generated in the first, ideation-oriented phase of learning (engage) and serves as an actionable research question that guides the student project as it moves into the investigate and act phases of challenge resolution.

Several academic professionals have published literature reviews of Challenge Based Learning interventions in higher education generally [9] and in undergraduate engineering programs specifically [10]. Other scholars have produced studies that analyze specific applications of the Challenge Based Learning framework in various engineering course settings [11]. For example, the study by Christopher Rowe and Stacy Klein-Gardner [12] examines how implementing Challenge Based Learning in a large introductory engineering course affected student learning. Because the course is taught in multiple class sections, the instructors were able to set up control and experimental groups of students. The control groups were taught by traditional lecture-based instruction, whereas the experimental groups engaged in Challenge Based Learning. The instructors collected and analyzed three kinds of data to test their hypothesis that Challenge Based Learning would produce enhanced student outcomes. Of the three data sets, which consisted of test results, survey responses, and written reflections, the student reflections showed the most variance in student outcomes that favored Challenge Based Learning approaches. According to the authors of the study, due to the formal structure of the Engage-Investigate-Act framework of Challenge Based Learning, students in the experimental group were better able to explain the elements of the design process they practiced in course projects as well as their reasons for selecting certain problem-solving approaches [12].

While studies like this one show the promise of Challenge Based Learning in introductory undergraduate engineering courses, the "essential questions" developed in the first phase of the framework are for the purposes of ideation so that students can identify and articulate an actionable research question to guide their work on a project going forward [8]. By contrast, the CEQs we have developed for the two semesters of our first-year engineering course are more reflective in orientation. They prompt students to identify and analyze opportunities for integrating perspectives in STS and engineering ethics into their approaches to engineering challenges. While drawing on broader experiential, challenge-based learning models, the CEQs play a role more similar to that of the Engineering Notebook described in a study by Joshua Luckens and Afsaneh Ghanavati [13]. The instructors developed the Notebook as a metacognitive and reflective tool "designed to deepen student engagement with essential questions aligned to the course's learning objectives" [p. 1]. Similarly, the CEQs in our course align with course objectives and are integrated into each design project in the first semester so that students gain proficiency in developing, analyzing, and implementing connections between the core values and skills expressed in the CEQs and the technical design work they perform in the various project modules.

Description of Intervention – Challenge Essential Questions

For this intervention, students were presented with the CEQs in three different ways: at the beginning of each module, integrated into the design process during each module, and as a reflection tool at the end of each module. At the start of each module, students were presented with the CEQs, which help them gain a better understanding of the problem they are solving (CEQ 1 and 2), assess and address potential impacts that possible design decisions could have (CEQ 4), help inform design decisions (CEQ 3), promote psychologically safe spaces while working together as a team (CEQ 5), and reinforce the importance of planning and clearly communicating the process to pertinent stakeholders (CEQ 6). Students were required to watch videos on key sociotechnical concepts such as ANT, sustainability, and character-based ethics, followed by a short quiz and class discussion, to provide further depth in understanding for each of these areas.

As students progressed through each module, they were again prompted to apply their understanding of the CEQ within the module framework. During this time, students included responses in class discussions and through small group discussions. Students were asked questions such as “How does this guide your design decisions?” and “How does this help you understand potential impacts of choosing one design over another?” Throughout these discussions, students were required to integrate the sociotechnical thinking in real-time to better understand the problem as well as during brainstorming, prototyping, and testing of designs.
At the end of each project module, students were asked to write a formal reflection applying the concepts expressed in the CEQ to the activity they just completed. The CEQs were formulated as a set of questions that provided prompts for their written reflections. Students were asked to choose two CEQ-based questions to answer at the end of each project module. The results from three sections of the first-semester course are analyzed below. While these questions were posed to students and incorporated into small and large group discussions throughout each module, we aimed to see students grow in their ability to apply the frameworks and concepts in the CEQs to support their answers in the written reflections more deeply as they gained practice with viewing their engineering challenges through this lens.

Results and Discussion

Each reflection assignment required students to address two of the CEQs of their choosing, along with a handful of more general feedback questions about the prior module and the skills acquired therein. The sixth CEQ is not included in the reflection assignments because the documentation and communication tasks were generally stipulated by the instructors for each project module; while discussion of CEQ 6 in class prompted conversations around the merits of different mediums (e.g., posters, written reports, etc.), it would likely not have promoted meaningful reflection. The frequencies of students choosing each CEQ are portrayed in Figure 1 below.

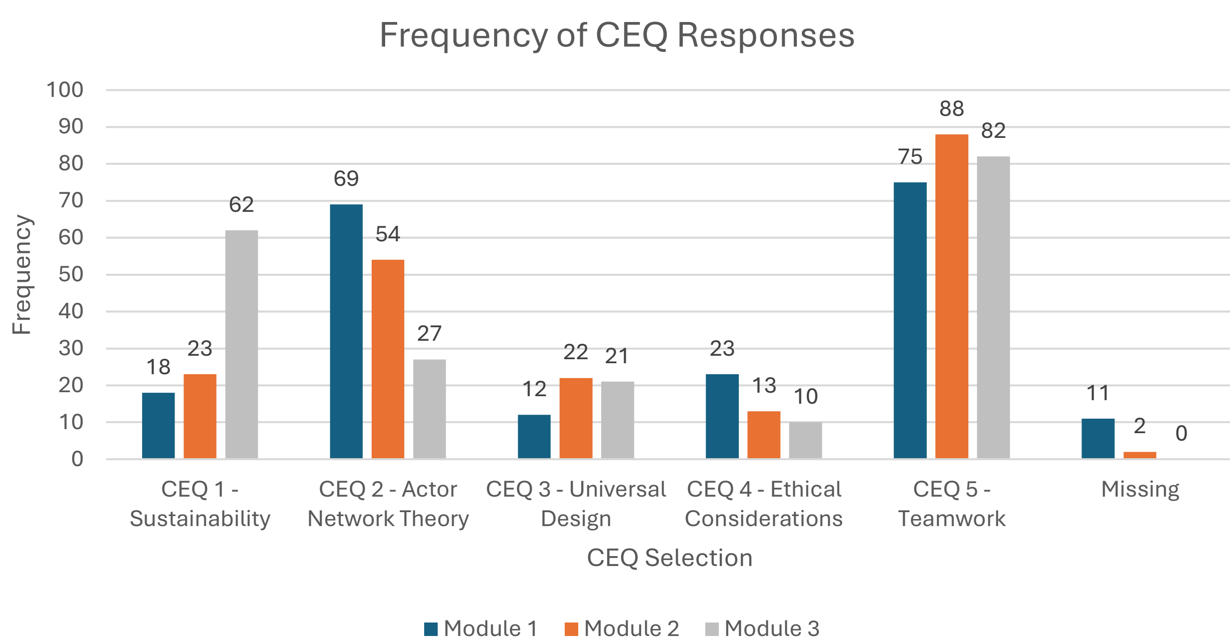

Figure 1: Frequency of CEQ Responses Across Submissions

As each student answered two CEQ prompts, the sum of the count will be double the number of students who submitted their reflections noted in the title of each table. The "missing" set notes students who submitted a reflection but neglected to answer one or more of the two CEQs they were asked to respond to. This was most common in the first reflection, but students quickly became more comfortable with the format of the assignment, and these missing entries dwindled to zero. Each round of reflection will be discussed individually before trends across the semester are examined. The Institutional Review Board approved the use of the reflection assignments, with students providing individual consent for the use of the text of their submissions.

Following the end of the first project module, the ANT and Teamwork questions were far and away the most popular choices for student reflections. This was not surprising, given that ANT had been the only CEQ topic formally introduced up to that point of the semester. The predominance of teamwork answers likely stems from the accessibility of the topic; almost every student had been on a team before and could think through what behaviors and expectations had defined their most recent project experience. As a result, the depth and quality of the responses to these two questions were among the best and most accurate. Students defined various actors involved in the project across the range of categories requested (e.g., technical, social, etc.), though the actors were often treated in isolation instead of as interconnected within the project network.

Many students still made attempts to answer questions one, three, and four all the same. Their answers were often their best guesses as to what each question was referring to. As most of these topics had not yet been covered in class, students were assessed on the thought put into their responses rather than the accuracy of them. Some of these reflections were on the right track but lacking detail, while others were incorrect. For example, ethical considerations were often applied within the context of the team environment. As one student shared:

> I kept in mind a couple of primary ethical considerations and implications, the first of which was fairness. I tried to make sure that everyone on my team got the opportunity to share and test their ideas... The second ethical consideration I kept in mind was honesty; our group made sure to keep our own ideas and not fudge the data...

Similar comments emerged about UD, with students reflecting on how they created an atmosphere in their groups where everyone could contribute evenly to their design. A student even described their experience drawing upon nature for inspiration as an example of UD, applying designs from other domains to their work. Other students connected both the sustainability concerns and ethical behavior to the minimization of resource usage throughout the first project. One student noted, "Our world doesn't have unlimited resources so it is important for engineers to be mindful of what and how much material they are using."

The second module's responses closely resemble the first, with a few minor changes. Teamwork became even more predominant, with eighty-eight responses versus seventy-five in the first reflection. ANT's popularity declined slightly, and UD became marginally more popular. These shifts may also have been related to shifts in course content. Although the primary focus of the second module was on the development of technical skills like programming, circuitry, and TinkerCAD, students were introduced to principles of effective, empathetic teamwork. This likely explains in part the increased number of student reflections on the teamwork-related CEQ. Additionally, students may have continued to favor ANT in their reflections because they were given the opportunity to apply the framework in a new project context, which was a different challenge. Exemplifying this, one student described having difficulty identifying the role one type of actor (natural actors in the environment) could play in such a technology-centric project:

> I think one part where I could do better would be to try and incorporate more natural actors to the assignment as there didn't seem to be many attached to this project but it seems unlikely for there not to be natural actors for a given assignment.

The comment highlights the need to continue to help students make conceptual connections between the sociotechnical frameworks and their work in the design projects. Regarding ANT specifically, as network builders students are responsible for successfully recruiting various actors, whether technical, social, natural, etc., to play certain roles in a project network to complete the assignment. In this case, electrons, a natural actor, have to be skillfully manipulated through the development of a wired electric circuit to serve the purposes of the students' design project.

By the third module, significantly more sociotechnical content had been introduced to the students. Specific lectures had introduced sustainability and UD principles, and an overview of character-based ethics had been presented. The focus of the third project was also intentionally and directly related to sustainability and accessibility, aiming to help students develop designs to address authentic needs in their local communities. As a result, it was unsurprising to see a shift away from ANT and towards sustainability in the CEQ choices. It seems logical that students would once again predominantly choose to write about what they had been thinking about most recently in the context of the prior module. Teamwork remained the most popular choice, however, likely due to the familiarity many students have with it as noted earlier.

Looking across the three iterations of this assignment, there are a few clear trends. Firstly, teamwork is a popular choice to reflect on, regardless of the content of the project or the most recent sociotechnical lecture and activity materials. While it is likely a topic familiar to many students due to prior experiences in high school and working with team members in this class, and others, it is also possible that the personal, experiential nature of the question was perceived as easier to reflect on. Rather than having to analyze their design process or project work, students could simply talk about their experiences over the previous weeks working with other students in a design team.

Another trend that emerged over the course of the semester was the alignment of students' choice of CEQs with the most recent sociotechnical content covered in the course. The pattern was most noticeable in the shift from ANT to sustainability as the secondary CEQ choice after teamwork between modules two and three. This finding is not surprising, as students were most likely choosing to reflect on what was most fresh in their minds. However, the more interesting facet of this pattern was that the increased choice of certain CEQs reflected a deepening understanding of the sociotechnical content over the course of the semester.

Whereas the first round of reflections often featured students' best estimates of what sustainability or UD were referring to, the final set of responses were more directed and better reasoned. As topics were introduced in class, students became more confident in applying them to their own work during the semester, and this was expressed in the quality of students' written reflections. For example, while a few students wrote about recycling in the first reflection, over half of the students were able to identify distinct connections to social, economic, and environmental sustainability in the third. Likewise, responses about UD shifted from inclusivity in a team environment to attention to the user's hypothetical needs. As one student concluded their response to the UD question, "Throughout this journey, our group maintained a strong focus on the principles of universal design, ensuring our solution was accessible, user-friendly, and sustainable, making it suitable for a wide range of users." In a sense, the first round of reflections collected a small subset of the students' pre-knowledge about the sociotechnical principles, which then deepened through explicit class instruction and integration into project work.

Conclusions and Future Work

Altogether, this intervention demonstrates that students could progressively engage in meaningful sociotechnical thinking within the context of design work. With additional rounds of reflection and more sociotechnical content being introduced in the classroom, students were able to broaden their perspectives and apply STS and ethical frameworks to varied design contexts. Along with a broadening understanding of how sociotechnical content is intertwined with engineering work, students' reflections got deeper over the course of the semester. Whether exploring additional facets of sustainability, keeping the user first in their design thinking, or synthesizing their teamwork experiences across three distinct projects and teams, providing the CEQ as a framework for students helped to promote more sustained sociotechnical reasoning and approaches to design challenges throughout the semester.

Therefore, in future courses, we will continue to embed CEQ into each module. However, there are two areas of improvement. First, we will build on and develop ways to meaningfully integrate instruction on sociotechnical frameworks throughout the course. Currently, students watch a video, take a short quiz, and then have a class discussion about some of the sociotechnical content. While effective, we want to build this library and identify ways to integrate concepts more seamlessly and frequently, with additional use of case studies to illustrate how the framework impacts engineering practice. Second, we aim to improve assessment of student responses by further developing analytical rubrics aimed at measuring student growth and understanding in each of the sociotechnical areas. Ideally, students will demonstrate mastery of incorporating the CEQ mindsets when they can incorporate the concepts unprompted. As we continue these iterations, we aim to inspire all students to further recognize and apply sociotechnical thinking throughout the engineering design process.

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