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Before Engineering: How do students consider social and technical dimensions when solving complex problems early in their academic engineering career?

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Abstract. Engineering education has made strides towards integrating social context into engineering problems. Real-world problems are one way educators have sought to contextualize technical problems; however, these problems are usually in capstone or design courses that students take later in their engineering coursework. Instead, students learn technical skills as abstracted from real-world applicability and later are challenged to reintegrate their technical skills within the physical, social, and economic environment. In this study, we seek to understand how students answer a real-world problem at the start of their academic engineering degree; specifically, students in this study are first-year engineering students who have completed one fall semester of their engineering degree. We have collected qualitative responses from 206 students in a survey administered at the start of their spring semester. Students were asked to lay out the process they would undergo to prepare for a natural disaster event in the problem. We collected qualitative student responses from two cohorts in 2019 and 2020. The findings show that while students focus primarily on the technical aspects of the problem, as apparent in the type of data they seek to collect, many include considerations on the people impacted, government interventions, and cultural values. This study sheds light on the ways that students answer a real-world problem before learning technical problem-solving techniques. The insights from this study will be used to supplement the introductory engineering curriculum, so students are better positioned to integrate social, economic, and political insights with their technical competencies in solving real-world problems.

Introduction

> "An engineer and a sociologist were tasked with finding the height of a church steeple. The engineer measured the angle to the top of the steeple and calculated the height using trigonometry. Then, to check the estimate, the engineer climbed to the top of the steeple, lowered a string until it touched the ground, climbed back down and measured the length of the string. The engineer compared the measurement to the estimate, calculated the standard error, and drafted a report documenting the methods and results. The sociologist bought the sexton a beer in the local pub and he told her how high the church steeple was" [1, p. 36].

As early as the first year of an engineering curriculum, students begin their socialization into engineering culture, in which they learn the rules and norms of the profession [2-4]. For students, this entry into professional socialization includes an implicit understanding of what constitutes 'evidence' to base engineering decisions [5-6]. The joke quoted in Donna Riley's *Engineering and Social Justice* synthesis lectures satirizes the engineer's method of 'brute force' problem-solving that ultimately takes much longer than the sociologist's method of valuing local knowledge. As an added value, the rapport between the sociologist and the sexton may prove helpful in future stages of the project that could require local engagement and community buy-in.

Students learn what counts as engineering knowledge in the engineering curriculum and can be quick to employ such 'brute force' methods of problem-solving. However, what perceptions of problem-solving are these students coming into engineering programs with? This study examines sociotechnical dimensions suggested by students in a real-world problem-solving exercise at the early stages of their academic engineering careers.

While several studies have documented a decline in engineering students' public engagement [7], sociotechnical thinking [8], and ethical considerations [9] from their first to final years in undergraduate engineering, there is less examination on students' complex problem-solving ability at these early points in their academic careers. Seemingly, students come in with a more integrated understanding of the technical and social dimensions in problems but learn through the curriculum what is valued and what is not in an engineering degree and profession [7], [10], [11].

In this study, we examine a case of problem-solving in a cohort of first-year engineering students. Students are presented with a real-world problem [12] at the beginning of an engineering course in their second semester and are tasked to write a response noting how they would solve it. This study is exploratory as we investigate the different methods and tools students propose to solve a complex problem about natural disasters.

Background

In engineering, students learn through socialization [13] which knowledge is valued and constitutes 'real' engineering and which knowledge should be bracketed away [7], [9]. In a culture of engineering, any political, social, or historical knowledge is deemed irrelevant in defining and solving the engineering problem [14], [15]. 'Real' engineering is made up of technical knowledge that can be reduced to mathematical calculations and abstracted from irreducible social knowledge. This separation creates a hierarchy between types of knowledge, a technical/social dualism within engineering, in which technical knowledge is valued over social dimensions [16], [17]. Students internalize these cues of what knowledge is valued in engineering as a part of their socialization [7], [16].

In engineering culture, technical knowledge is taken to be rational and objective. Engineers place similar values on social advancement structures which reinforces their meritocratic ideology that those who persist in engineering do so because of their hard work and talent [10], [18] rather than their intergenerational wealth [19] and privilege [20]. Students learn these cultural cues

either through overt or implicit messages passed onto them by faculty, the curriculum, institutional cues, or other forms of professional identity socialization [21].
Engineering education reinforces the dualism between the social and technical dimensions of engineering. The social dimensions, partly required by ABET accreditation through engineering ethics, remain segregated from 'real' engineering [22]. In many of these standalone ethics modules or courses, students internalize their 'dis(integration)' from engineering and have rated ethics as "the least interesting, the least useful, and the most trivial" part of their engineering curriculum [7], [23. p. 347].

Sociotechnical integration has been examined in engineering education by several scholars, many of them cited above. Leydens et al. describe sociotechnical integration as a student's ability to address the "interplay between relevant social and technical factors in the problem to be solved" [8]. The terms social and technical also require definition. For this research study, we use the delimits put forth by Erickson and colleagues, in which the 'social' is a broader term that refers to the economic, environmental, ethical, and safety decisions of a problem, while the 'technical' references aspects that can be reduced to be solved with scientific and mathematical tools [24]. Much of engineering education's focus elevates the technical over the social dimensions [7], [16]. This hierarchy is explicit in degree requirements and grading rubrics [25] and perpetuated through cultural norms around rigor [11]. Without a critical examination of the social dimensions external to and within the technical dimensions, engineering decisions can embed unchecked implicit assumptions that can disenfranchise those without power [26].

Research Design

In this study, we seek to understand how students think about answering a real-world problem before learning various technical skill sets in their engineering degree. The overarching research question addressed in this study is: How do students use technical and social knowledge to answer an example real-world engineering problem? The terms social and technical can have multiple meanings, so we adapt definitions put forth by Erickson, Claussen, Leydens, Johnson, and Tsai for this paper [24]. The 'social' encompasses the economic, environmental, ethical, and safety decisions, while the technical refers to aspects of problems that can be reduced to be solved with scientific and mathematical tools [24].

Methods

This study was conducted in the second week of a first-year engineering course required for every student pursuing a degree in engineering. This course is an introductory engineering class and required for all 200 first-year engineering students at a private research university in the Northeastern region of the United States. Students do have the option of taking a placement exam to opt-out of this requirement. Additionally, students interested in engineering and studying engineering-related majors like engineering psychology or physics have also been enrolled in this first-year engineering course. The composition of these students by major is shown in table 1, which includes a designation as School of Engineering or Arts & Sciences.

Table 1. The intended major and school designation (Engineering or Arts & Sciences) of students in 2019 and 2020.

	Intended Major	*Students*
Engineering	Mechanical Engineering	64
	Biomedical Engineering	47
	Civil and Environmental Engineering	34
	Chemical Engineering	24
	Electrical Engineering	16
	Computer Engineering	12
	Human Factors Engineering	12
	Data Science	2
	Environmental Health Engineering	2
	Architectural Studies Engineering	1
	Computer Science	5
Arts & Sciences	Computer Science	4
	Engineering Psychology	4
	Physics	1

Table 2. The difference in question wording between spring 2019 and 2020 surveys

	'Real-World' Question
2019	What tools would you use to analyze historical natural disaster response patterns in an effort to decrease response time and increase resource availability immediately following a natural disaster? Start by determining what information you would collect, and then explore the tools/analysis techniques you would apply to that information in order to draw a meaningful conclusion.
2020	Imagine that you are a data scientist working for the World Health Organization. Propose a plan to analyze historical natural disaster response patterns in an effort to decrease response time and increase resource availability immediately following a natural disaster. Be sure to list what information you would collect, and describe the analysis steps you would use to draw a meaningful conclusion.

Data Collection

The data collection consisted of surveys administered in the second week of the spring semester. The survey collected data relating to students' intended majors and an open response to a real-world problem around natural disasters shown below. This research is a part of a more extensive study examined in [27], [28]. Based on the responses from students in the spring of 2019, the wording of the question in spring 2020 was changed to include more person-first language. In the 2019 question, there was the potential for the wording of "What tools would you use" and "Start by determining what information" to connotate that there are correct and incorrect tools and information. In the 2020 question, the wording was changed to "Imagine that you are" and "Propose a plan" to suggest that there is no single correct answer.

The survey was administered to students through a homework assignment in the course's learning management system and was marked for completion. IRB approval was obtained for this study. In 2019, we collected 83 student responses. In 2020, we collected 128 student responses.

Data Analysis

Using the definitions of the 'social' and 'technical' provided by Ericksson et al., as well as the vast array of other scholars working in sociotechnical pedagogy [29] - [34], we engaged in two rounds of iterative inductive coding on the student responses. In the first round of coding, we open-coded the responses, which generated upwards of 300 codes. In the second round of coding, we categorized the open codes as social or technical considerations. These codes were organized along an axis of social to technical and another axis of problem-focused data collection to solution-focused analysis and communication. Figure 1 displays the final codes along the two axes. Table 3 shows the final codebook we used in examining student responses with the social to technical alignment.

Limitations

There are several limitations to this research design. Most importantly, the question under investigation in this paper was the final question of a 30-minute survey. Survey fatigue may have played a role in how the students answered the question. Additionally, the two questions preceding this question were on writing code to solve a simple, abstracted close-ended problem. This sequence of questions may have primed students to address the natural disaster question with more emphasis on its technical dimensions.

Another limitation of this study is the lack of demographic data collected. Research building on this study will include demographic questions to discern whether students who have historically been excluded from engineering are more likely to offer social considerations in response to this type of question.

Lastly, the survey was administered as a low-stakes homework assignment in an introductory engineering education course. This avenue of delivery can be a strength because students had room to express dimensions they may not have in a high-stakes engineering assessment. However, because the survey took place in an engineering course, the students may have been approaching the question from preconceived notions of what it means to be an engineer. The context surrounding this question's delivery is crucial to unpack, which is why we present these current findings as preliminary research rather than as absolute determinations of how students negotiate social and technical dimensions of problems in their responses.

Findings

First-year engineering students solved the real-world example problem in a variety of ways. These responses ranged from incorporating social and technical dimensions in their problem scoping and data analysis method. Students detailed various social and technical dimensions in understanding the problem and then how they would arrive at and communicate the solution. These social and technical dimensions varied in their use in understanding the problem or proposing a solution. Still, broadly, students discussed more social considerations in their formation of the problem and more technical tools in their solution space. As stated previously, we use the definition stated in Ericksson et al. for social and technical. The 'social' encompasses the economic, environmental, ethical, and safety decisions. The 'technical' refers to problems that can be reduced to be solved with scientific and mathematical tools.

In this section, we have categorized these various themes as social and technical dimensions, with the disclaimer that several of the themes do fall into both categories. We acknowledge that in our research into students' social/technical dualism, we must be cautious not to draw stark boundaries that serve to perpetuate dichotomies between social and technical dimensions of engineering. The social to technical codes are presented in table 3, with code descriptions and example quotes. In this table, we also show the number of times each social or technical dimension theme was mentioned in the student responses. We found that the divide between the social and technical dimensions was similar to the social dimensions mentioned 88 times and technical dimensions 101 times. Note that we are cautious about quantifying these qualitative responses but provide these code frequencies to show aggregate the social to the technical distribution of students' responses. Following the table, we describe the qualitative findings in further detail.

Table 3. Social to technical codes with corresponding description and example quotes (2019-2020)

	Code	Dimension description	Example quote
Social	*Mention of people (35)**	Students explicitly talking about people	"the least people were hurt"; "replace the homes of the people"
	Government (8)	Contextual understandings of a region's government system	"I would also want information on the type of government system, cultural values about trust in the government system."
	Culture (2)	Understanding of local community	"So, I would have a specific group of people work with the community to understand their needs."
	Economics (36)	Region's economy	"If the region is poor and far away from the city and tends to get natural disasters then build more hospitals, shelters, and come up with ways to combat the natural disaster."
	Cost/Money (7)	Cost of response measures, cost of damages incurred	"How much money was put into the response….(ex. more capital investment leads to better resources available and shorter response time) I could submit a report suggesting certain methods that would improve the situation (ex. allocate more money for immediate disaster relief)."
	Create a protocol (20)	Develop a prescriptive framework for how to proceed	"Then, I would have a code or protocol to determine what is actually needed for each natural disaster."
	Existing standards (48)	Using predetermined references or standards	"I would pair this information with how strong the disaster was statistically (ex. category of hurricane, strength of earthquake on richter scale, etc.)"
	Technological innovation (9)	Emphasis on new, cheaper, faster, better technology to ameliorate impact	"Recent innovations and innovations in progress that could improve response time and resource availability."
Technical	*Modeling, Coding, Programming (24)*	Referencing modeling, coding, or programing to find relationships between variables	"You can write a code that analyzes historical data about natural disasters, and the amount of time it took to respond and supply for natural disasters"

(#)* = number of response segments under this code

Social Dimensions

Students mentioned social dimensions more so in explanations around how they would collect data than how they would analyze the data. Interestingly, many students explicitly mentioned people in their answers. Other students used euphemisms like *"fatalities"* or "*mortality rates*" rather than explicitly mentioning people in their answers.

Students also noted a need to understand broader contextualization. One student noted the need to identify "*the type of government system, cultural values about trust in the government system*." Another student noted that they would "*have a specific group of people work in the community to understand their needs*." These students prioritized relationships between the local community and their government and that of the local community and the student's team. Another broader social dimension that some students noted was that of the region's economy. One student in particular wrote:

> *"If the region is poor and far away from the city and tends to get natural disasters then build more hospitals, shelters, and come up with ways to combat the natural disaster."*

In a similar vein, another student focused more on the "*money* [that] *was put into the* [disaster] *response*." This student explained their assumption in their response in that "*more capital investment leads to better resources available and shorter response time*." This student went on to note that they would suggest best practices based on this monetary research and then suggest improvements. A suggested improvement was to *"allocate more money for immediate disaster relief*." In the more economic-driven suggestion, this student, as well as others, had already predetermined that a solution would be to increase the amount of money spent to alleviate the disaster's impact. Additionally, many of the measures that students used to determine the impact of the disaster were reduced to costs in damages. We categorize these economic and monetary aspects more in line with technical dimensions, for they are reducible measures that can be solved with scientific and mathematical tools.

Technical Dimensions

Students predominantly used technical dimensions in describing their methods for data analysis, solution selection, and application. The themes under technical dimensions are detailed in table 3. One recurring theme was the use of coding or programming as a way to find an optimal solution. In this theme, a student's response stated: "*you can write a code that analyzes historical data about natural disasters, and the amount of time it took to respond and supply for natural disasters.*" Another student noted that they *"would write a program that analyzes how quickly the reaction time is for natural disaster response."*

In a related category, students noted that they would create a model. One student stated that they *"would compile all of* [their] *data, looking at the trends where countries were most prepared for disasters, and* [they] *would model* [their] *conclusion off of that*." Another student noted that they *"would plot on a graph/map each location that provides relief for natural disasters… and find a way to measure the resources each has available. Then* [they] *would have a code or protocol to determine what is actually needed for each natural disaster."*

In the coding and modeling themes, students relied on their professed ability to gather data from some specified and unspecified data and analyze its trends through a model, potentially through coding. Seemingly, this analysis would yield some inferences for them to conclude from. In these cases, the students outlined linear processes as their proposed responses.

In the data collection realm of the process, some students noted that they would "*define the different categories of disasters*" as an initial step. For a particular student, "*once* [they] *had all of the data* [they] *could begin to put it into numbers such as response times, lives lost, people rescued.*" Interestingly, this student included mention of broader issues "*that could influence response times such as climate, severity of disaster, and access to supplies.*" The student notes that they would use all of this data to "*formulate a plan and predict the level of response needed for worse disasters.*" Like the plan formulation, other students mentioned a protocol they would create to inform future disaster responses.

Some of these protocols were the product of the data manipulation, but in others, students considered the context in which they would exist. One student's response was that the protocol would be "*simple and straightforward*" in thinking of the protocol's future users. One student's contextualization of the plan surfaced in their response, in which they would have "*an email regarding the people who need to be involved already written* [to] *send them as soon as a natural disaster happens.*" These particular themes are not reducible to be solved by math and science tools but are examples of normative, top-down solutions that rely on numerical data to decide and justify a course of action.

Lastly, students pointed to technological innovations as ways to respond to future natural disasters. One student noted that in their research of past disasters, they "*would make sure to focus on more recent disasters as the technology during those time periods would most closely mirror current technology* [...] *due to advancements in technology*." In a related response, the student highlighted "*recent innovations and innovations in progress that could improve response time and resource availability.*" In these responses, students centered on technology and had displayed assumptions of technology's benevolence [35, p. 140] in aiding in a natural disaster.

In figure 1, we have organized the themes along a spectrum of social to technical and problem to solution space to show the themes in relation to one another. The rounded shapes depict dimensions that were more in line with the social, while the trapezoid shapes show dimensions more in line with the technical.

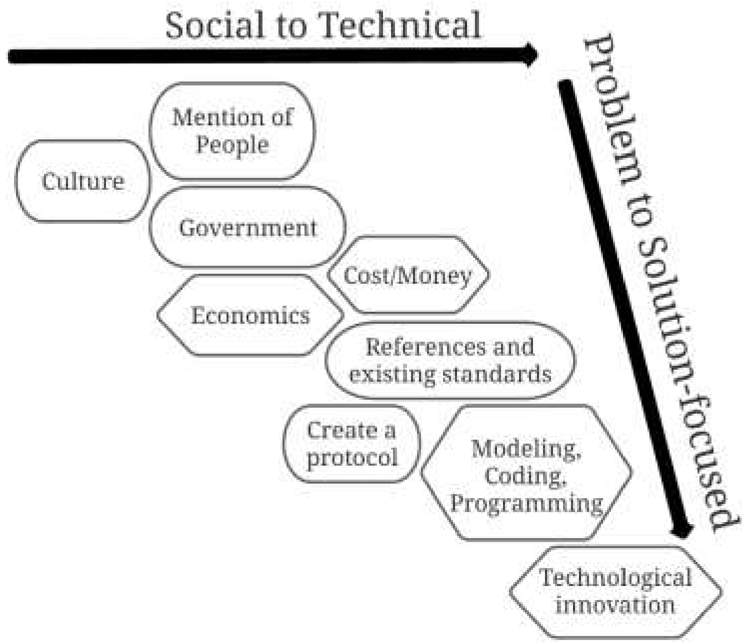

Figure 1. Student response codes along social to technical and problem to solution-focused axes.

Discussion

Students displayed a range of social and technical dimensions offered in their responses to the natural disaster question. Even though the survey was administered in an engineering course and following two close-ended programming questions, many students still included social considerations in their responses that paralleled their technical considerations. Interestingly and perhaps unsurprisingly, the range of social to technical dimensions offered by students were focused more on the problem space than in the solutions space. However, we must remind the reader that with this work, we do not seek to draw strict boundaries between the different dimensions—social, technical, problem-focused, solution-focused. Such boundaries would serve to perpetuate social/technical dualisms in engineering as well as reduce the student responses to piecemeal categorization. The students did not follow a linear process between the problem to the solution, nor were the social considerations neatly distinguishable from the technical approaches.

While a linear process was not evident, the first-year engineering students' focus on the problem space is noteworthy. Problem definition in engineering problem solving has been a critical aim of sociotechnical pedagogy as its framing sits to overcome the technical/social dualisms in engineering culture [7], [30]. While students from this study may not be deliberately focusing on the problem and the solution, their descriptions address different aspects of this process. In the space of problem definition, some students went so far as to propose learning about the local community's needs and conducting interviews with those affected in past disasters. These proposed actions would help students understand the problem through different vantage points and supplemented with lessons around situated knowledge [36] and community-driven design [37].

Another approach students proposed in the problem space was to collect as much data as was available on past disasters. The student proposals that focused on collecting as much data as possible were far less specific than those that addressed communities or culture through interviews or relationship building. In some instances, students did specify the variables they would collect, and in others, they sought to collect all that was available. This study highlights many students' preconceptions of what 'data' implies and has the power to reveal. Broader societal claims around data (big data, data science, etc.) parallel this tendency to overvalue data as an idea rather than be specifically based on disciplinary or local context. This emphasis on data also exists in academic environments such as national funding agencies' proposals toward harnessing the data revolution [38], institutions increasing their use of terms like 'data-driven decisions' [39], and academic programs in data science becoming increasingly popular [40].

The preliminary findings from this study tell us that many of the students have internalized this idea of data without a critical understanding of its details and limitations. In future courses, the process of gathering data could be discussed as considerations around classification [41], [42], discipline-specific methodologies for collecting data [43], critiquing existing datasets [44], and their practices of collection [45].

The last theme we will examine in this paper is how students discussed cost and money in their responses. Importantly, the students' use of the theme varied when they focused on the problem—e.g., using cost to understand and categorize the extent of damage from past disasters—or solution—e.g., by allocating more funds for future disasters. However, in both cases, students are quick to use the cost of the disaster to represent the nonreducible aspects of the problem or greater allocated funds to solve issues around preparation and response. While there were students who coupled financial parameters with social dimensions such as cultural values, trust in the government, or communicating the solution, the students who offered more technical responses overall let cost encompass the social dimensions of a natural disaster. While the integration of cost with technical aspects of engineering is nothing new,[1] it is an important preconception of what first-year engineering students see as in the bounds of engineering [46].

Overall, students come into their first year of engineering education with presuppositions of who and what engineers are and do. In many ways, as students learn about what engineering is and is not, they are beginning to fit themselves into their conception of what it means to be an engineer. While past research in engineering tells us that the narrowness of the field can be limiting for

[1] In 1886, Henry Towne, a professional mechanical engineering and future president of ASME, raised the importance of integrating cost into engineering calculations during his address to Purdue engineering graduates. In it, he stated that “the dollar is the final term in every engineering equation” (Towne cited in [47 p. 37]).

students who try to bring their entire identities into engineering [9], [48], [49], the inclusion and valuation of social considerations may help students bring in their previous knowledge and lived experiences into the discipline [16], [17]. In so doing, students may become participants in reframing engineering as a sociotechnical endeavor.

Future Research

Many of the social dimensions that students included in their responses are an interesting departure from the majority of data they proposed to collect—data that can be reduced to mathematical calculations (e.g., disaster cost, response time, lives lost). Notably, the wording of the question in both years used terms such as tools or data scientist to frame the task, which may have contributed to the emphasis on quantitative data analyzed with mathematical tools. Still, students emphasized a range of social dimensions that were, quite frankly, surprising. While in an engineering classroom context, the students' operationalization of words such as data and tools may have been more technical, there is room for research on the social dimensions offered by these first-year engineering students. We pose two questions for further research, (1) what prior knowledge and lived experiences these students have to have included comments such as cultural values and community needs in their proposal, and (2) how can we as engineering educators integrate their prior knowledge within the engineering curriculum?

Conclusions and Implications

Understanding the various dimensions in complex problem solving is helpful to learn about where the students are in their learning and how they are beginning to organize their learning in engineering. These findings are preliminary and a way to gain insight into student assumptions and conceptualizations in complex problem solving early in their academic careers. From this study, we see that the idea that engineering is a sociotechnical process is not new for many first-year engineering students. Instead, we have learned that as engineering educators and researchers, we should strive to build upon the funds of knowledge students bring into the engineering classroom, specifically their proposed social dimensions. Many of the students can address various social dimensions of engineering work in a low-stakes, open-ended engineering problem administered in the form of a survey.

With this work, we set out to understand the ways first-year engineering students addressed a complex engineering problem through a sociotechnical lens. With these insights, we seek to build upon their funds of social knowledge and design a responsive first-year engineering curriculum that elevates the social and cultural dimensions of engineering such that they are on equal footing with the technical dimensions.

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