Ethical Considerations in Biomedical Engineering: Qualitative Student Perspectives from a Large Mid-Western University

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Abstract— Engineering curricula provide students with opportunities to construct their understanding of what constitutes ethical engineering practice. This study examines how biomedical engineering (BME) students conceptualize ethics in a biomedical engineering context. Our previous work-in-progress study identified ten ethical considerations salient to biomedical engineering faculty members' incorporation of ethics into their program: Economic, Environmental, Interpersonal, Legal, Organizational, Personal, Professional, Societal, Technological, and Theoretical. This study extends that work by determining how these ethical considerations were present in biomedical engineering students' conceptualizations of ethics in biomedical engineering. We interviewed four senior-level biomedical engineering students nearing graduation from the same program in a large Midwestern university in the United States. Five individuals from engineering education or biomedical engineering backgrounds reviewed these interviews in an iterative and collaborative process. Findings from this study include a revised set of ethical considerations. This study can facilitate future dialogue on ethical considerations in the context of biomedical engineering and, we hope, engineering ethics more broadly.

Keywords—engineering ethics, biomedical engineering

I. INTRODUCTION

Since ABET revamped student outcomes in 2000 to include an explicit ethics outcome, engineering ethics has been a required student outcome in accredited engineering education programs [1]. Despite the necessity of including ethics in engineering curriculums, limited feedback from ABET reviews regarding ethics instruction leads to uncertainty regarding how much content is necessary to meet this criterion [2]. As ABET does not provide direct guidance on how to teach nor assess ethics, the teaching of engineering ethics can vary widely from program to program. This study seeks to extend prior work to understand how a set of ethical considerations manifest among biomedical engineering students at a single university site.

A. Variations in Ways of Teaching Engineering Ethics

While there are some common trends in how ethics is taught in engineering [3], [4], common content foci vary by discipline. For example, Bielefeldt et al. [5] compared differences in topics taught to engineering students by discipline and found that, when compared to civil engineering, safety was a primary focus of chemical engineering. In contrast, environmental protection was a more concerted focus of environmental engineering. Biomedical engineering curriculums were much less likely to incorporate sustainability considerations. Moreover, Bielefeldt et al. [6] found that bioethics, RCR, and nanotechnology were more common in biomedical engineering than in other engineering disciplines.While disciplinary distinctions may lead to distinct instructional trends, individual faculty may also teach ethics in distinct ways. For example, Bielefeldt et al. [7] explored how demographic patterns led to different pedagogical strategies. They found that women faculty in engineering were more likely to implement discussion and reflection-based teaching strategies, and underrepresented faculty were more likely to integrate social justice as an ethical framework.

There exist many models for conceptualizing ethics at a broad level. One of the most oft-used frameworks comes from Herkert [3], who offers two primary approaches to ethics: micro-ethics and macro-ethics. Micro-ethics draws attention to personal considerations and interpersonal relationships. In contrast, macro-ethics in engineering draws attention to the "collective social responsibility of the profession and to societal decisions about technology" [3, p. 205]. Herkert's key objective was to encourage a more concerted focus on macro-ethics in engineering education. The micro/macro framing has been used by others, including in BME [6]. However, this framing is also not exhaustive. For example, meta-ethics offers another lens that focuses on ethical principles, philosophies, or moral theories [8].

Katz explored individual faculty mental models in three disciplines: civil engineering, electrical engineering, and mechanical engineering [9]. Katz identified *ten* areas of variation in faculty mental models of engineering ethics education. Mental models highlighted variation in ten areas, including definitions of engineering ethics, ethics topics, learning goals, where students learn ethics, when students learn ethics, when ethics is taught, who decides what content to teach, who actually teaches ethics, how faculty teach, and how students learn. Example definitions (the first mental model area) include 1) professional responsibilities or *"*the standard of conduct agreed upon by the professional engineering community*"*; 2) social responsibilities; 3) community standards or norms of *one's "*professional community*"*; 4) legality or *"*intellectual property, copyright, etc.*"*; 5) research ethics or *"*responsible conduct of research*"*; 6) micro ethics or *"*day-to-day scenarios*"*; 7) macro-ethics or *"*large issues that engineering as a profession faces*"*; and 8) codes of ethics. Importantly, these definitions overlap and influence ethics topics (the second mental model

area) that faculty perceive as important. Example topics include professional ethics, social responsibilities, social issues, academic ethics, legal ethics, research ethics, micro ethics, macro ethics, and codes of ethics. While presented discretely, mental model areas overlap. For example, if one defines ethics as involving macro-ethical concerns, the ethics topics they discuss are likely to include macro-ethical concerns.

B. Ethical Considerations in a Biomedical Engineering Program at a Single University

This study continues a focus on the ethics of biomedical engineering by extending a coding framework that identified primary ethical considerations integrated across a curriculum in a single program [10]. Our prior work began with Katz's [9] theoretical mental model areas, especially the *topics* that engineering faculty considered important for engineering ethics education. While Katz's framework offered a useful starting point, we recognize that context matters. Specifically, we recognized that our data was from a biomedical engineering program, Katz did not include Biomedical Engineering faculty in their study, and thus the list of topics might differ from the topics that Katz presented.

Moreover, we shifted from a focus on 'topics' to 'considerations,' recognizing that our data included aspects of engineering that the faculty directed students to *consider* in their ethics assignments – thus, while Katz studied *engineering ethics education*, the list of considerations we offer are directed towards *engineering ethics*.

Our previous analysis started with Katz's mental models of ethics topics and used these to code language in syllabi and ethics curricular materials. After generating a list of considerations based on these curricular materials, we reviewed faculty interviews to confirm that these considerations were of ethical import to the faculty. Ethical considerations represented topics that faculty perceived to have import for teaching biomedical engineering students to become ethical, make ethical decisions, or act ethically in their discipline or profession. See [10] for more information.

II. Study Overview

This study builds on our prior findings to explore and integrate the student voice into a set of ethical considerations described by biomedical engineering faculty at a single university [10]. We analyze interviews with a small sample – four students – who were at the end of their undergraduate collegiate journey. Thus, our findings provide evidence of how, exactly, these students gave voice to the manifestation of these ethical considerations. They also suggest which considerations students were most cognizant of as they left academia and entered their profession. Thus, first and foremost, this paper serves as a check regarding to what extent and in what ways students internalized the ethical considerations targeted in curricular objectives and activities. Through our analysis, we also identify additional perspectives students brought to or gleaned from their curricular experience. We utilize these to make the considerations more precise or add considerations as needed. Accordingly, we pose the following two research questions: 1) To what extent can we reliably use the ethical considerations to identify the presence of the ethical considerations in the student interviews? and 2) How do students give voice to these considerations?

III. Methods

A. Biomedical Engineering Ethics Curriculum

For the past four years, faculty members at a Large Midwestern Urban University have participated in a Faculty Learning Community designed to support the integration of ethics across the departmental curriculum [11]. The first FLC sessions were guided by Palmer's theory presented in The Heart of A Teacher – "we teach who we are" [12, p. 1]. Palmer argued that "good teaching cannot be reduced to technique; good teaching comes from the identity and integrity of the teacher" [12, p. 2]. Accordingly, FLC members were engaged in critical reflection activities to understand how their identity undergirded their practices and beliefs as an educator.

Throughout the remainder of the FLC, faculty revised course curricula by developing course assignments and activities to infuse ethics throughout the program. At the time of data collection, undergraduate students in the program had participated revised courses for up to three years, thus experiencing ethics across the curriculum. Examples of the revised courses include a lab course that explores the ethics of animal testing and the biomedical engineering capstone course (see [10]). More details are provided in [13].

B. Participant Recruitment & Overview

To recruit participants, the first and second authors virtually attended the biomedical engineering capstone course and invited students to complete a survey. This survey was administered to all students participating in any course offered by an FLC participant. Students were informed that they would have the option to indicate their interest in volunteering for an interview at the end of the survey. We offered all biomedical students who indicated their interest in interviewing the opportunity to participate. Four biomedical engineering senior students participated in an interview. Each of these students participated in multiple courses revised by the FLC participants. Participants included three males and one female. Participants were pseudonymized as Adam, Brice, Camille, and Devon.

C. Data Collection

The first author conducted interviews at the beginning of Summer 2021. The interview protocol was derived from the protocol we used when interviewing FLC faculty participants. The interview included five sections: motivation for pursuing a biomedical engineering degree, ethics in biomedical engineering, ethics in engineering design, ethics and community engagement, and explicit perceptions of ethical considerations (the list included considerations developed in the prior study). While the first four sections involved open-ended responses, in the fifth section, students responded to the previously identified set of ethical considerations. Students were asked to review the ten ethical considerations and discuss the most important and least important considerations in the context of biomedical engineering. This section was included at the end of the interview to minimize interview bias. Thus, most of the interview did not provide students with this explicit language. However, by explicitly including the list, we sought to identify

whether the considerations were understandable to students and how they would prioritize them in practice. The prompt asked:

> Please think about how important these items are to consider for ethical practice in your discipline. Please take a few minutes to read through the items. If any are unclear, please let me know. When you are ready, I would be interested to hear which items are the **three most important** and which are the **three least important**.

Due to the pandemic, each interview was conducted virtually and recorded via video conferencing software. The audio was isolated from the video recording and sent to a transcription service. The interview transcripts were the basis for our analysis.

D. Data Analysis

Coding proceeded in multiple rounds. In Round 1, Author 1 coded student interviews using a deductive coding approach (i.e., the set of ten ethical considerations identified in [10]). Author 1 extracted all coded passages, and Author 2 reviewed all of Author 1's coding instances. Authors 1 and 2 next discussed instances of disagreement and identified potential revisions to the ethical considerations. In Round 2, Author 1 revisited and updated coded passages. Here, Author 1 again extracted the coded instances and then shared these portions with Authors 3 and 4, who reviewed and agreed or disagreed with the coded transcript excerpts. After their review, the authors met to discuss challenges and update code definitions.

In Round 3, the authors utilized the updated codes, and each author performed another analysis. Here, Authors 1, 2, 3, 4, and another coder (a graduate teaching assistant in biomedical engineering) each coded all quotes from the prior session but with the updated understandings. Whereas in Round 2 Authors 3 and 4 could see Author 1's codes, here, all authors coded with a blank slate mentality. This step aimed to finalize agreement across our collective interpretations of each code within the student data. The authors then met to discuss their experience coding and interrogate considerations that remained challenging based on disagreements between coding. Thus, this conversation served to identify inconsistencies in the interpretations of the ethical considerations and informed the final revision of the ethical considerations that we share in this manuscript.

This final description of considerations was guided by instances of agreement among three or more authors. Here, we present updated considerations and exemplary instances from high levels of coder agreement. As a final check, all authors reviewed the exemplary quotes in this paper and confirmed each quote based on their view of the final ethical considerations.

E. Quality Considerations

We pursued **procedural validation** [14] by designing our interview protocol based on prior theory (I.e., the list of considerations described in [10] and mental models in Katz [9]). The interview prompted students to reflect on their perception of how one ought to live and act ethically and describe how that relates to biomedical engineering practice. Second, **communicative validation** [14, p. 640] was sought by introducing students to the exact list of ethical considerations derived from faculty data to understand if those considerations resonated with their conceptualization of ethical biomedical engineering practice. Students quickly understood and spoke to the considerations. Third, **pragmatic validation** [14, p. 641] was developed by establishing applicability of the codes by both faculty and students. Fourth, **process reliability** [14] was sought by engaging five coders with unique perspectives. Through three rounds of coding, however, we found that arriving at a shared agreement regarding the application and scope of each consideration was difficult. In this study, we were confident in sharing exemplary quotes where four of five coders agreed, but we have ongoing challenges with several considerations that we candidly share in the results. Finally, **theoretical validation** [14] was established by scoping each ethical consideration to be sufficiently distinct while also capturing the variety of ways students described the consideration. At this stage, we felt confident in stating that each consideration warranted distinction and offered distinct discourses by which students and faculty described ethical practice in biomedical engineering.

F. Limitations and Future Work

This study includes a small set of students at a single university. Thus, we do not suggest that these considerations encompass all potential ethical considerations in biomedical engineering or engineering broadly. Future work ought to identify the applicability of these considerations to other engineering curriculums. Others might apply the considerations as a lens to identify student outcomes associated with ethics resulting from faculty members' integration of ethics across their curriculum via existing artifacts, such as exit interviews, ethics-related assignments, or course observations. Our prior study did not address relative (de)prioritization of considerations and we do not directly focus on this here. Future quantitative work might consider the relative prioritization of considerations.

Table I: Updated Descriptions of Ethical Considerations

Ethical Consideration	Description
Economic	Engineering ethics involves considerations pertaining to money or other forms of capital.
Environmental	Engineering ethics involves considering engineers' impact on the environment, especially concerning reducing environmental waste.
Caring for Humans *(Revised from "Interpersonal)*	Engineering ethics involves considering what actions or situations promote care for humans.
Legal	Engineering ethics involves considering the law.
Personal	Engineering ethics involves personal considerations.
Organizational	Engineering ethics involves considering organizational culture.
Professional Responsibility *(Revised from "Professional")*	Engineering ethics involves thinking about necessary or good practices associated with being a professional in my discipline.
Societal	Engineering ethics involves considering social contexts.
Technological Design	Engineering ethics involves thinking about the technologies that engineers develop, manufacture, or produce and (often) their impacts.
Frameworks of Ethics *(Revised from "Theoretical")*	Engineering ethics involves thinking about a set of ethical perspectives, heuristics, or principles that serve as a framework for guiding ethical action.

IV. Results

Findings from this study include a set of ten ethical considerations, revised from the set of ethical considerations previously derived from faculty data. Notably, we did not revise *Economic, Legal, Personal, Organizational,* and *Societal*. We summarize these considerations in Table 1. Next, we describe 1) revisions to ethical considerations, 2) how students gave voice to the considerations, and, when applicable, and 3) challenges we experienced while coding and revising each consideration.

A. Economic

1) Revisions: We did not make any changes to the *Economic* consideration. Thus, we offer the original description: **Engineering ethics involves considerations pertaining to money or other forms of capital.**

2) Examples in the Student Voice: Students discussed *how* product accessibility varies based on socioeconomic factors, the role of funding and profitability in product development, and implementation concerns. Regarding how socioeconomic factors impact access to a product or service, Adam shared:

> …taking into consideration our population that had to be low cost, that was a big thing, so keeping it under $50 as a lot of the people that our sponsor works with don't come from great financial... don't come from great social standing or financial standing, I guess. – *Adam*

Later in the interview, Adam shared another perspective and discussed a hypothetical situation where a biomedical engineer might consider their users' socioeconomic status:

> If you're designing one for a lower-income population that is going to be fully covered by insurance or just the base insurance, then you probably don't want to make one that has some sophisticated biological or electric components […] [If] it was just a hook or something that still improves their quality of life but does so with a price point that they would be able to afford. - *Adam*

Second, students examined the impact of funding availability and the ethics of profitability. Brice shared how funding opportunities can influence the scope of engineering work, a consideration he made during his senior design project:

> …it was also very small population. The chances of getting a lot of funding for clinical testing might be very small even the future. I think there were some ethical considerations in terms of what materials do we make this out of? - *Brice*

Adam explored the tension and need to balance between company profit and product accessibility. As he shared, "Just like if you make the product cheaper, then it ends up maybe hurting the company's performance but is able to reach more of a greater population." Camille shared challenges with the tendency of business, which she viewed as prioritizing profitability over the accessibility of medical services:

> …right now, I think it's absolutely incredible how expensive getting a medical treatment is or getting prescriptions and whatnot, especially without insurance for some people. I think a lot of decisions need to be based on economics, and I think a lot of decisions right now are based on personal growth and making more money. - *Camille*

B. Environmental

1) Revisions: Students primarily discussed waste reduction and proper resource usage during product development. Thus, we revised the description from "Engineering ethics considers the environment" [10, p. 2] to **Engineering ethics considers engineers' impact on the environment, especially reducing environmental waste.**

2) Description: Brice felt that biomedical engineering designers should consider waste reduction and offered questions that biomedical engineers might consider to this end:

> But even just with design changes, I think one of the big things that comes to mind is the example mentioned at the beginning was cutting down waste. As the person who's designing the product, you can design it with that in mind. What is the total lifecycle of this product? How can I make sure that I'm minimizing the environmental impact? - *Brice*

While not focusing directly on waste reduction, Adam reflected on his senior design project and discussed the tension between promoting environmentally conscious practices while simultaneously staying economically competitive:

> … we had a device that was 3D printed, and we did 3D printed mini-iterations along the whole design process. It ended up being where you could see that a larger company where prototyping is a lot more prevalent and used even greater. You could see how this compilation of a lot of plastic could be detrimental just because... and also because all this 3D printing plastic is nonrecyclable, so there definitely was some consideration there. - *Adam*

Here, Adam's specific environmental concern resulted from the non-recyclability of the material they selected, and how 3D printed products require considering the product's lifecycle.

Students acknowledged that *Environmental* considerations overlap with other considerations as well. For example, Adam articulated the overlap between *Economic* and *Environmental* considerations with respect to the performance and cost of ventilation systems. Brice suggested that environmental considerations overlap with *Caring for Humans*, and described how his courses in the program were "reminding us to reduce waste where possible, but at the same time, prioritize patient safety." As Brice stated, even if one prioritizes environmental concerns, "sometimes it's necessary to use one-time sterile devices. So, there might be unavoidable waste."

3) Challenges: In the original set of ethical considerations, we understood concerns about animal rights to be *Environmental* considerations, as faculty discussed how animal testing impacts communities in nature and how to be respectful therein. However, students often considered animal testing in the context of the responsible conduct of research. We coded such passages as *Professional Responsibility*.

C. Caring for Humans

1) Revisions: Our analysis revealed that the *Interpersonal* consideration were not sufficiently specific to capture how students addressed user and stakeholder concerns. Thus, we revised this consideration to *Caring for Humans*,

described as **engineering ethics involves considering what actions or situations promote care for humans.**

2) Description: Students articulated their concern about caring for human users and stakeholders. These concerns encompassed ensuring their understanding of users' experience, typically achieved through need-finding. For example, Adam shared, "You've got to make sure that [the product] it's meeting the needs of the people that you are making it for or designing it for." Similarly, Camille shared, "I think it's very important for an engineer to understand exactly what the device is going to be used for and who the users are." Students elaborated by sharing how design decisions were informed by the user group characteristics. Camille's design team worked with a pediatric population. She shared, "So I think it's very important to know who the user is and what their needs are [...] if it were to be used on adults [rather than kids], we would have made other design decisions." Similarly, Adam shared, "Knowing that a patient, a pediatric patient nonetheless, would have to be able to operate our device, so it couldn't be super crazy complex to use."

Safety was a common way students expressed their care for humans. Brice shared how his design team sought to promote patient comfort despite the added challenge: "The comfort of the patient that was something that was foremost in our mind when we looked at using soft materials over hard materials, even though that made the design process a little trickier."

Camille discussed how prioritizing *Economic* and *Personal* considerations, such as profitability and designer preferences, could contribute to a lack of *Care for Humans*. As she shared:

> The ethical decisions we're making, we can make decisions based on, we're going to get a profit out of it, or we think it looks cooler this way, but in the end, if it's not really benefiting the user, if it's making it more expensive for them, that's not ethical. - *Camille*

Considerations are not mutually exclusive. *Caring for Humans* often involved students' consideration of the impact of engineering technology captured by *Technological Design.* Our coding discussions questioned whether *Caring for Humans* and *Technological Design* are intrinsically entangled and thus impossible to separate. For now, we differentiate *Caring for Humans* from *Technological Design* by, where the former focuses on the actions that promote care for humans and the latter focuses on the ethical implications of technological design (which may or may not involve *Care for Humans*).

3) Challenges: This code entailed a significant revision to the prior *Interpersonal* consideration. Our discussions highlight the complexity of human interactions and relationships, including the inability to code students' feelings. *Caring for Humans* now emphasizes the behavioral component of Interpersonal interactions. We explicitly include the word humans to differentiate between human concerns and animal concerns, as we struggled to identify whether students were viewing animals as resources or animals as agentic or autonomous beings with rights. In Round 3 of coding, when students mentioned animals, we agreed that these passages generally better aligned with *Professional Responsibilities*, wherein students focused on responsible research practices.

D. Legal

1) Revisions: We did not make any changes to the *Legal* consideration. Thus, we share the original description: **Engineering ethics involves considering the law.**

2) Description: Students described how *Legal* considerations included compliance with product design regulations and preventing negative self-consequences.

Students identified and discussed the legal implications of complying with standards offered by the U.S. Food and Drug Administration and the International Organization for Standardization. Adam described how complying with regulations can lead to safe products, stating, "We definitely deal with legal considerations that our device was following FDA, not FDA as much for us, but ISO regulations for biocompatibility, that the material that we're using was safe and that the design was safer." Camille challenged the sufficiency of *Legal* considerations. Specifically, she discussed the 510(k) process, a process used to demonstrate that a new product is "substantially equivalent, to a legally marketed device" [15]:

> … I don't think that 510(k) should even be a thing. All of them need to be going through pre-market approval [...] Because they do the whole, if it's substantially equivalent or whatever, but some of these devices are getting on the market for being substantially equivalent to a device that is already recalled and proven not to work. - *Camille*

Devon addressed the concerns about preventing negative *Legal* self-consequence after product implementation. Devon questioned, "What happens if it doesn't function as it's supposed to? What if it breaks? Are you going to get sued?" Devon indicated that professors drew student attention to these concerns, and as a result, their design team "reached out to the law school and talked to some patent people."

Legal had limited overlap with other categories. In one instance, Devon highlighted that regulatory compliance is not only a *Legal* consideration but also can align with *Care for Humans* by promoting the safety of new products. During the explicit portion of the interview wherein students were provided the prior list of considerations, Adam indicated that legal was aligned with organizational in that both were 'procedural' or offered procedures to guide ethical approaches. Devon similarly recognized how legal considerations might align with his future experiences in his company, including how FDA regulations may influence "testing" procedures.

3) Challenges: Instances where three coders coded a quote but two coders did not included passages focused on 1) "sueing" others, 2) policies associated with animal testing, and 3) mentions of device recalls. Many of these codes associated with *Legal* were limited in detail and the brevity of student responses led to uncertainty in applying codes to such quotes.

E. Organizational

1) Revisions: Organizational considerations were minimal in student data (at least in instances where four or more coders agreed). We retained the prior description: **Engineering ethics involves considering organizational culture.**

2) Description: Previous examples of "Organizational" in the faculty data included examples related to organizational values, codes, or procedures. Most students did not speak specifically to these examples. Students sometimes briefly considered organizations from an organizational systems perspective. Only in one instance did four coders agree to the presence of this consideration in student data. Adam discussed organizational considerations that may impact how a company decides the "price point" in an ethical manner. Adam stated:

> I definitely thought a little bit with economical at the end of senior design, just trying to think if this device were ever to be a commercial product, where do you set the price point? If you can manufacture it for a certain amount, how much profit, what should the price point be set at to still allow a great amount of people to be able to access it, but also enough to make sure that your company is able to function properly and that employees are paid to a level at which they should be with their worth. - *Adam*

3) Challenges: The few *Organizational* considerations in the data suggest a potential need to provide students with more tools to consider how organizational culture may influence their future ethical engineering practice.

F. Personal

1) Revisions: We did not make any changes to the *Personal* consideration. Thus, we offer the original description: **Engineering ethics involves personal considerations.**

2) Description: Students described how *Personal* considerations inform ethical action through 1) consulting personal beliefs, 2) considering personal morals, and 3) reflecting on learning experiences. First, students discussed how personal beliefs play a role in what one views as ethical. For example, Brice shared how personal beliefs can inform whether one perceives something as ethical or not, even in a professional setting. He shared that personal beliefs play a role in "deciding who you work for, and what projects you're willing to work on, and being willing, if necessary to put your job on the line, if you feel that something is unethical that you're being asked to participate in." Devon shared a conversation from class about receiving a vaccine: "We discuss everyone has their own choice. No one is forced to get the shot. It's all up to their own beliefs of whether or not it will do more good than harm." Here, Devon's response hints at how *Personal* considerations overlap with considerations of Frameworks of Ethics, noting that individuals can have understandings of what constitutes "more good than harm."

Second, students shared how personal morals inform how one lives ethically. Camille shared, "I would say it comes down to the person thinking, I am right for these reasons because this is morally what I believe." Yet, Adam discussed how *Personal* considerations cannot be the only consideration when determining how to live or act ethically. He shared, "you can't just take your own beliefs and take them for the end all be all."

Finally, students shared how reflecting on their personal experiences may inform ethical action. For example, Brice shared how the outcomes of his previous actions and his morals informed how he determined ethical courses of action.

Personal overlapped with *Care for Humans* in two instances. Both instances occurred during the interview section where students responded to the original list of considerations. Camille explicitly mentioned deprioritizing her values but then spoke to a specific personal value that involved *Care for Humans*. Here, Camille seemed to struggle with a tension of one's personal values versus the need to act as a professional:

> … a lot of these decisions for BME are made with respect to other people. I guess the decisions that are made, you need to be okay with making them, that they align with your morals and whatnot, but I don't think it matters in the long run what you actually believe. It's more of what's going to benefit the recipient. […] I know there could be times when a patient asks for something, depending on what field I end up in, and I may not agree with their decision, but as their doctor [a potential career choice], I have to do it. - *Camille*

Camille later unpacked this tension in more detail, thus questioning her gut assessment. As Camille shared:

> Personal could come into play a little more. I think my opinion really stems from thinking about different medical situations that I don't agree with. […] I think personal, that may come into play with more engineers, thinking it has to align with their beliefs for them to make the decision, but my mindset is more, it doesn't matter what your beliefs are if it's not doing good for the recipient. - *Camille*

3) Challenges: Personal was one of the codes where four or five coders most often agreed, but there were many instances where only two or three individuals coded. These latter passages often were succinct but spoke broadly to the import of individual viewpoints, upbringing, and self-perception of what constitutes ethics. Yet, many of these quotes did not explicitly verbalize that these considerations were important for *ethics in biomedical engineering*. Thus, we posit that the primary challenges stemmed from a lack of direct connection to the biomedical engineering profession or engineering ethics.

G. Professional Responsibility

1) Revisions: We revised the original *Professional* code to *Professional Responsibility*. We also elaborated on the description to better capture the ways that the students voiced the biomedical engineering discipline. Accordingly, we revised the description from "engineering ethics involves thinking about good practices associated with being a professional in my discipline" [10, p. 3] to "**Engineering ethics involves thinking about necessary or good practices associated with being a professional in my discipline."**

2) Description: Students voiced *Professional Responsibility* as fulfilling engineering duties and conducting responsible research. First, students acknowledged that people trust engineers to make decisions that promote safety and reduce the potential for harm. Brice highlighted how others trust engineers' work to be safe. He described, "you're trusting that the elevator you're in or something is not going to just plummet, that people that have done the engineering that will be safe and did the maintenance that is specified for it to be done to make sure that stays safe." Relatedly, Adam shared that others trust engineers to design products that are safe. As he shared, "As an engineer, people put their trust in you to make

decisions about products and stuff that people just assume are not going to be super detrimental to their health or anything."

Second, students described how engineers conduct responsible research. Devon shared engineers must conduct sufficient research to reduce potential harm, stating:

> ... you're not just throwing something out there that hasn't been tested before. You're not just throwing a pacemaker in someone, and this is the first pacemaker anyone's ever made. You're not putting someone at risk for your own knowledge or learning experience. - *Devon*

Camille explored the necessity of sufficient research before introducing products to the market by reflecting on a documentary describing misdiagnoses resulting from a hip implant, where "not enough trials were done. The engineers didn't do enough to make sure the decisions they were making to put this on the market were right. They didn't do enough."

Students also pondered the ethics of animal testing. Brice noted complexities associated with engaging in responsible animal testing, highlighting the animals' experience. He shared: "what degree of causing inconvenience or pain to animals in the course of laboratory testing for human benefit, where do you draw that line exactly?" Devon discussed that respect is key to conducting responsible animal testing, stating, "you kill the animal. That's the big ethical dilemma there. Then once you're over that and then once you have the body, you can do whatever you want with it as long as it's respectful to the animal." Brice similarly discussed the need to design effective tests to obtain sufficient results in fewer attempts. As Brice stated:

> For a few different courses, we've had to look into the ethics of animal testing… And so I feel like that gave me some more tools for understanding how to better design and experiment to reduce the amount of animals we're using, while still getting good results. - *Brice*

3) Challenges: The consideration "*Professional,*" as defined in our previous work, was difficult to apply here. The term felt too broadly applicable to students' discussion of ethical biomedical engineering practice. Thus, some coders saw the prior scope everywhere. The current framing more concertedly focus on the *obligations* of biomedical engineers.

H. Societal

1) Revisions: We did not revise the *Societal* consideration. Thus, we offer the original description: **Engineering ethics involves considering social contexts.**

2) Description: Students discussed how global implications, social systems, and cultural knowledge comprised *Societal* considerations. First, students described how engineers must consider the scope of engineering work and its large-scale impact. As students described the global impact of engineering, they also highlighted how the *Societal* consideration is entangled with other ethical considerations. For example, Brice described how engineers must consider a global community in design, stating: "There's global implications. So, there's also kind of a global community in terms of your device is going to cost energy to produce." Brice connected this consideration to *Environmental*, stating, "It's going to produce waste, and you have an obligation as much as possible to reduce that." Similarly, Camille shared, "From an engineering point of view, we have to understand that the decisions we make are going to affect a large amount of people, for the most part."

Students recognized that designing at a large scale comes with challenges. Adam shared his concerns about the possibility of negative impacts: "How much of a population... If a population is being negatively affected by a new product, then if they're having pretty severe side effects... Well, for one, what is too severe? What is a severe side effect?" Adam believed that some negative impacts are unavoidable in biomedical engineering. He shared, "Some population of people are going to be negatively affected, and that's kind of the unfortunate reality I feel of the BME industry, but it's something also to strive for to make that number lower and lower."

Students describe considering extant social and cultural systems. For example, Brice recognized that localized impacts could occur based on the context where a product is introduced: "I think on one level, you're dealing with a very localized community setting of what's going to be the local impact of your product where it's used."

Students also discussed the importance of considering cultural values. Camille highlighted an engineer's responsibility to consider the backgrounds of the individuals they were designing for. Devon shared this concern then cited specific cultural considerations an engineer might make:

> I think a lot of decisions that people make that are worldwide decisions, if they don't have the background, there's no way they're going to make an ethical decision that does more good than harm when they just don't know." […] when they started using pig heart valves for people is... Well, it's also Muslims and the Jewish people who can't use those. So it's like you're only helping one set of people. If you're just talking about the three main religions, you're only helping a third of the population as opposed to like if you were to artificially print using like stem cells or something that is made within someone's body or just like plastic or polymer or something like that. - *Devon*

3) Challenges: While we did not revise the prior *Societal* consideration, we found that it was difficult to distinguish between *Interpersonal* and *Societal* in our original set of considerations. We aimed to distinguish between these two by revising *Interpersonal* to *Care for Humans*, while focusing *Societal* considerations to those associated with social systems.

I. Technological Design

1) Revisions: After analyzing the student data, we revised *Technological* to *Technological Design* to include both the impact of new technologies and the process by which the technology was developed. By expanding the title to include the word Design, we broadened this consideration to emphasize elements of design (e.g., manufacturing, idea generation, project scoping via constraints). Thus, **engineering ethics involves thinking about the technologies that engineers develop, manufacture, or produce and (often) their impacts.**

2) Description: Students considered the ethics of new technologies. Adam shared his thoughts on the ethical outcomes of innovations, stating, "I think sometimes a new

technology can be detrimental when existing technology was plenty fine." He continued this line of thought, sharing:

> I think sometimes all these companies just want to innovate constantly when there might already be a product that is as good as you're going to get for... So, you might be kind of over engineering or over thinking a product that has already been very helpful and doesn't need to be innovative at all. - *Adam*

Students also considered the outcomes of (ethical) testing procedures, as described in the *Professional Responsibility* section. Students described the importance of testing newly designed technologies but recognized that testing might not emulate exactly how technologies are used. For example, Devon reflected on a documentary and said, "But then with metal-on-metal hip implants, they've done testing and they've seen the pros outweigh the cons, but then once they implement it in people, then they started seeing new side effects and stuff." Devon revisited this idea and shared a hypothetical example that highlights how engineers might consider tertiary impacts, not only on users but other stakeholders. As Devon asked, "What happens when that person dies? Their body will only decompose so much and then they're just going to have this medical device sitting in the ground." Devon questioned, "Is that going to affect satellites or phone wires and stuff like that?"

3) Challenges: Because design is fundamental to engineering [16], we found it difficult to apply our original *Technological* consideration due to the number of examples students shared about designing technology. We found that students were often considering the impact of technology as well as the ethics of how technologies were designed. Thus, we added the word "design" to the consideration and emphasized the latter. We also identified many instances that overlapped with other considerations, which was not surprising as as many design activities (e.g., need-finding, testing) often relate to other considerations, such as *Caring for Humans* and *Professional Responsibility*.

J. Frameworks of Ethics

1) Revisions: We revised the prior *Theoretical* code to *Frameworks of Ethics*, thus expanding the scope to not only include explicit mentions of theory but other heuristics and perspectives that students considered important for ethical practice. We thus revised the description to **engineering ethics involves thinking about ethical perspectives, heuristics, or principles to guide ethical awareness and decision-making.**

2) Description: Students described heuristics that can inform ethical actions and decision-making. Brice described the importance of an accessible ethical framework: "I think also, having a very strong understanding of some kind of objective framework you can use to evaluate moral decisions and ethical decisions is something that's going to promote ethics." Students most often considered Utilitarianism by describing the most good for the largest number of people. For example, Camille shared, "I think personally, I make more decisions based on if it's going to help more people." Similarly, Devon shared:

> I think ethical to me is like doing what's good for the greater good of people. So it's like if it's going to... Like animal testing. Some people don't find that ethical, but it's like if you're testing on rats as opposed to humans right away, you're going to save a lot of people's lives going through the trial and error of something that doesn't work. - *Devon*

1) Challenges: Students rarely described ethical frameworks, and when they did so, it was often brief. However, students often shared language that speaks to Utilitarianism (e.g., "doing good") as well as Non-Maleficence (e.g., "minimizing harm"). However, students usually employed such language as a heuristic rather than the result of synthesizing a situation from that theoretical lens. Students also offered other frameworks. For example, Brice described "The Golden Rule" (i.e., treat others as you want to be treated) and other students often mentioned macro-ethical concerns. For the future, coding for specific ethical frameworks may be a better coding strategy.

V. Closing Discussion

This study examined how ethical considerations identified in faculty interviews [10] were present in students' discussion of ethical BME practice. We sought to identify whether the considerations we identified in faculty's curricular materials (see [10]) were present and identifiable in the student data. *Economic*, *Legal*, *Organizational*, *Personal*, and *Societal* were not revised, but all other considerations were updated to better represent students' conceptualization of ethical biomedical engineering ethics. Thus, our analysis suggested that students described similar considerations as faculty members when discussing what constitutes ethics in biomedical engineering. The presence of similar ethical considerations in student interview data suggests that students' beliefs about what is important to biomedical engineering practice were either informed by or reinforced by their classroom experience.

We argue that differing curricular experiences may influence what students believe is important to ethical biomedical engineering practice, and thus offer this more specific focus on students' curricular experiences as a lens for future work. While each student enters the classroom with a unique set of experiences, we call attention to the impact of educators' values, beliefs, and (in turn) teaching practices on students' ethical development. Thus, we encourage instructors to engage with the mantra, "We Teach Who We Are" similar to FLC members involved in this overall study [11]. For example, faculty members discussed industry mission statements they were familiar with and described industry culture [10] as important for ethics in biomedical engineering. Yet, students may not have substantial experience with and, consequently, ideas about how organizational culture may influence ethical biomedical engineering conduct [17]. Accordingly, we urge instructors to not only consider how their experiences might be shaping the way that they present course content to students, but also to prompt students to become aware of the ethical considerations, including their experiential sources and how they may engage ethical considerations in their future careers.

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