What is Biomedical Engineering? Insights from Qualitative Analysis of Definitions Written by Undergraduate Students

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Abstract

Discussions regarding the identity of Biomedical Engineering (BME) have been on-going since its inception as a profession over 50 years ago. Recently, these conversations have taken on increased importance in response to calls for improving BME undergraduate education, especially for students interested in industry work after graduation. At last year's ASEE Annual Conference, Biomedical Engineering Division programming concluded with a discussion of how the lack of a universal BME identity contributes to uncertainty on the part of potential employers. The development of a coherent field identity is dependent on a shared understanding of the field by the major stakeholders, namely students, academic departments, accreditation bodies, national governing organizations, and industry partners / potential employers. Unfortunately, the perspectives of the foremost of these stakeholders have largely been ignored in conversations of cultivating a BME identity as no previous study has examined how undergraduate students define BME.

Therefore, to contribute another important voice to these on-going conversations, this paper presents a qualitative analysis of definitions of BME written by 115 undergraduate students at a large R1 public university in the Midwest. In vivo qualitative coding and categorization revealed five main features of these definitions exemplified by "impact", "design", "apply/use", "understand/combination", and "undefined" labels. Comparison of pre-BME students (those who had not previously completed a core BME course) and within-BME students (those who had successfully completed at least one core BME course) showed a transition from an impact-focused definition of BME to a more application-focused definition. Within-BME students were also more likely to acknowledge the interdisciplinary nature of BME by including other fields beyond engineering in their definitions, most commonly medicine and biology. Finally, the results of the qualitative analysis are discussed in the context of ABET bioengineering/BME program-specific criteria to add to on-going work on how BME identity may be developed during an undergraduate program. This work represents an important initial step in addressing the alignment of stakeholder understanding of BME and also may have important implications for student recruitment and retention.

Introduction

The establishment of undergraduate biomedical engineering (BME) programs in the late 1960s makes it a relatively new educational option compared to traditional disciplines such as mechanical, electrical, or chemical engineering [1]–[3]. Despite slow growth through the 1990s, there has been a significant increase in the number of undergraduate BME programs and degrees conferred in recent years [1], [2], [4], [5]. Over that time, increasing numbers of BME departments and educators have had to make important decisions regarding how best to educate students in this ever-evolving, interdisciplinary field. In perhaps the earliest report on BME education, Harmon described the field in 1975 as "a relatively new interdisciplinary profession striving for identity, quality control, and acceptance" [6, pg. 89]. He went on to say that while there was wide recognition of the "great need for biomedical engineers" there was little consensus on "how to educate one, or even what is meant by a biomedical engineer" [6, pg. 89].

Over 40 years later, discussions of what BME is and how best to design a BME undergraduate education are still on-going. The interdisciplinary nature of BME coupled with its recent substantial growth have resulted in disparate undergraduate curricula across institutions and a lack of a shared understanding of BME identity [3], [5], [7]–[9]. This absence of shared understanding between higher education and industry has been implicated in the difficulties BME undergraduates face in securing employment [3], [5]–[9]. However, addressing this absence of shared understanding has proven difficult without a consistent message from the field itself including academic departments, accreditation bodies, and governing organizations.

Analysis of the definitions of BME given by various stakeholders helps identify "conceptual imprecisions" [10, pg. 3] that contribute to this lack of shared understanding and misaligned identities. Discussion of definitions is critically important for educators as it lends insights into the philosophy of the educational system, including its objectives and the methods used to accomplish those objectives [10]. However, the perceptions of one major stakeholder have largely been ignored in these conversations of BME, especially when it comes to undergraduate education – the undergraduate students themselves. The authors know of no previous report that examined how students define the field or practice of BME. Therefore, the purpose of this paper is to present a systematic exploration the definitions of BME written by undergraduate students to contribute another voice to important on-going conversations surrounding BME identity and BME undergraduate education.

Background

Even in Harmon's 1975 report it was acknowledged that the variety of approaches to BME education being adopted could result in graduates being "unattractive on the job market" as their capabilities would be unclear to potential employers [3], [5]–[9]. Flexibility and diversity in *how* degree programs structure and implement their BME curriculum (often based on faculty expertise and resource availability) is seen as necessary for such a broad, interdisciplinary field [1], [5], [8]. However, a lack of consistency in *what* is taught is seen as the main impediment to industry stakeholders fully understanding what they can expect from BME graduates [3], [5], [7]–[9]. Identification of the specific topics and content that should compose this foundational BME knowledge has been the focus of many studies, reports, and initiatives [2], [6], [9], [11], including the NSF-supported Vanderbilt-Northwestern-Texas-Harvard/MIT Engineering Research Center (VaNTH ERC) for Bioengineering Educational Technologies [5], [7], [8], [12]–[14].

A first step in developing a consensus regarding what core content should be included in a degree program is a consensus on the field to which the degree program belongs. Cheville described the importance of a shared understanding of engineering, but the same can be applied to the specific discipline of BME [10, pg. 3]:

> "...for engineering educators the definitions of engineering do matter since they inform what we should do. Definitions also point out potential conceptual imprecisions; if we do not interpret a definition the same way then there is a potential for miscommunication and subsidiary ideas may themselves be imprecise. Mitcham and Schatzberg [15] point out that definitions are fundamental to philosophy, and our philosophy, whether explicit or not, determines how we educate [16]. More practically, definitions serve as objectives, helping to determine the ultimate aims of education. Thus, definitions may provide insights into how and why engineering education is this way and not that."

As Linsenmeier states in his 2003 IEEE article on biomedical engineering [5], "in order to specify curriculum, we need to specify the field in which we are trying to provide an education (pg. 33)." Indeed, many of the reports offering suggestions for core BME content begin with a description of biomedical engineering and how it is distinct from [5], [6], or synonymous with [1], [2], [9], bioengineering. These discussions of nuanced, sometimes described as unimportant, differences between "biomedical engineering" and "bioengineering" are emblematic of the need for a consistent understanding of BME; an understanding that can unite the field under a coherent identity and inform the ultimate objectives of BME education.

Some authors turn to definitions given by the Biomedical Engineering Society [2], [9], the Whitaker Foundation [2], [5], [9], and/or the National Institutes of Health [5], [9] to inform their description of BME (these organization-provided definitions are included in the discussion). While these definitions are largely consistent in that all three mention engineering, biology, and medicine, there are also important differences that are discussed in the appendix. As the authors of this study are principally concerned with the education of BME undergraduates, this work utilizes a discussion framework based on how ABET defines BME in terms of the expected capabilities of BME and bioengineering graduates [17]. The program-specific criteria differentiate BME and bioengineering from other engineering degree programs and are required of all ABET accredited BME or bioengineering programs. Accordingly, they have also been used to inform suggestions of core BME content [5], [9], [18]. Harris et al. suggests that while the ABET criteria are general, the accreditation system has promise to help develop the identity, quality control, and acceptance as discussed by Harmon in 1975 [2], [6].

Research Questions

Student perceptions are equally as important as organizational definitions when seeking to cultivate a shared understanding of the field; as students of BME, they will become the next practitioners of BME. Cheville's assertion above also suggests that student definitions may indicate how the perceptions held by educators are reflected in their philosophy and teaching approach [10]. Understanding how students see a field also has important implications for recruitment and retention (e.g., students may be less likely to persist in a degree program if their perception of the field is grossly different than that being promoted by the department). However, student perceptions of BME have received limited attention with almost no previous work explicitly examining how students themselves define BME. Therefore, utilizing a mixed-methods study design, the long-term goal of this work is to explore the relationship between a student's definition of BME, their motivation to study BME, their degree expectations, and their career beliefs and goals. The results presented in this specific report are those of the initial qualitative phase of the study; definitions of BME given by 115 undergraduate students interested in BME were analyzed to address the following research questions: *How do interested undergraduate students define biomedical engineering? and, How do the definitions of students who have not taken a BME core course differ from those who have completed at least one such course?* It is the authors' hope that this paper (1) encourages other BME undergraduate programs to undertake similar work at their institution, (2) identifies potential topics and questions for future study in BME education, and (3) motivates interest in exploring how students' perception of the field may influence their choice to enroll or persist in an undergraduate BME program.

Methods

Study Design

The authors adopted a sequential, exploratory mixed-methods study design to meet the long-term research goal stated above; this report will specifically focus on the results of the initial qualitative phase of this work relative to the italicized research questions. The use of mixed-methods in engineering education research has expanded significantly over the past ten years [19]–[21] as appreciation for the advantages of integrating the results of both quantitative and qualitative methodologies has grown [20], [22]–[24]. As the name suggests, sequential exploratory studies typically involve exploring a phenomenon qualitatively to identify important variables for subsequent quantitative study [20]–[23]. In the specific variation of exploratory mixed-methods research proposed here, the analysis of qualitative data will lead to the development of specific hypotheses that will then be tested quantitatively to demonstrate generalizability [20], [22].

Data Collection

Over the first two weeks of the fall 2018 semester, a total of 115 undergraduate students at a large R1 public university in the Midwest provided handwritten, anonymous responses to the following prompt: "In your own words, what is biomedical engineering?" Sixty of these students had not yet completed a core BME course and therefore formed a "pre-BME" group for comparison. Responses for this group were collected from students enrolled in a biotechnology-focused Introduction to Engineering course (n = 47, 57% freshman and 43% sophomores by credit) and students who attended the orientation event for newly declared BME majors (n = 13, 85% sophomores and 15% juniors by credit). It should be noted that there are approximately 20 versions of the Introduction to Engineering course offered, each with a unique focus. First-year engineering students are free to choose in which version to enroll based on interest and schedule availability; they do not formally declare a major until at least the end of their first semester. Based on the published timeline for the degree program, the students in this comparison group are expected to be in their first and third semesters.

The remaining 55 students were all enrolled in a core BME course which had at least one other core BME course as a pre-requisite and therefore made up a "within-BME" group for comparison. Responses for this group were collected from students enrolled in a BME undergraduate laboratory course (n = 42, 25% juniors and 75% seniors by credit) and students enrolled in the first semester of a year-long BME senior design capstone course (n = 13, 100% seniors by credit). As the laboratory course serves as a pre-requisite for the design course, there was no overlap in these two student populations. Based on the published timeline for the degree program, the students in this comparison group are expected to be in their fifth and seventh semesters. The details of the student participant populations are summarized in Table 1.

Table 1. Populations of students who provided written definitions of biomedical engineering

Student Group	**Individual Student Population**	**Class Standing by Credit**			
		Freshman	**Sophomore**	**Junior**	**Senior**
Pre-BME (n = 60)	Introduction to Engineering	**27**	**20**	0	0
	Orientation for Newly Declared BME Majors	0	**11**	**2**	0
Within-BME (n = 55)	BME Undergraduate Laboratory	0	0	**10**	**32**
	BME Senior Capstone Design	0	0	0	**13**

The definitions written by newly declared and senior design students were collected with responses to two additional open-ended questions (listed below) which probed motivations and perceived opportunities related to their BME undergraduate degree. For this subset of 26 students, their responses to these questions provided some context for discussion of the student-provided definitions of BME.

- Why did you choose to pursue a biomedical engineering undergraduate degree?
- What types of jobs/opportunities do you think are available to students that graduate with a BME undergraduate degree?

Data Analysis

Coding is a qualitative research methodology in which words or short phrases (i.e., "codes") are used to summarize or represent the salient meaning of text-based data. This allows for more in-depth analysis of qualitative data by distilling the main features of written passages, such as the student definitions collected in this study [25]. Although a number of coding techniques are used by qualitative researchers, the succinct nature of the student definitions motivated the use of a collaborative in vivo coding approach. In this coding procedure, multiple researchers are tasked with identifying the key words or phrases found directly in the written work to be analyzed [25].

Results

Research Question 1: How do interested undergraduate students define biomedical engineering?

The 26 definitions given by newly declared BME majors and BME senior design students were treated as the modeling data set for coding. These definitions were initially coded by the first author and a junior BME undergraduate student using an in vivo approach. After independent identification of recurring words or phrases, the two coders came together to create a list of these in vivo codes and organize them into exclusive categories, each with their own description and inclusion criteria. For example, phrases such as “developing tools” and “creating devices” were both organized under “design” which was defined by the coders as the design or development of something new. To confirm consistent interpretation and application of these categories, each coder analyzed the modeling data set again and any discrepancies between them were discussed until 100% agreement was achieved. The final collaborative book of codes contained 5 major categories, 2 of which could be further divided based on the specific disciplines included in a definition (Table 2).

The remaining 89 definitions (given by students enrolled in either the Introduction to Engineering or BME undergraduate laboratory course) were treated as the validation or test data set. Both coders independently coded these 89 definitions using the collaborative code book and reported the number of times they identified each of the 13 categories. For each student population in the validation data set, MedCalc (version 18.10.2, MedCalc Software, Belgium) was used to calculate the intra-class correlation coefficient (ICC) between the frequencies reported by each coder; an absolute agreement two-way random effects model was utilized to demonstrate inter-rater reliability [26]–[28].

To demonstrate the in vivo coding and categorization procedure, a sampling of student definitions and the assigned codes/categories are shown in Table 3. It is important to note that a single definition may be coded into multiple categories depending on the specific phrases it includes. As previously stated, the newly declared and senior design students’ responses to the additional open-ended questions were not analyzed directly; instead, these responses provided context for discussion of the associated student population definition of BME.

Table 2. Specific codes and organizing categories which emerged from qualitative coding of student definitions of BME (italic text lists the words or phrases identified during in vivo coding)

Category	Code(s)	Description
Impact	Impact	Student definition of BME includes the potential to impact medicine, health, or humanity *(improve, further, benefit, help; solve/address problems/issues)*
Design	Design	Student defines BME as the design/development of something new *(develop/create/design/engineer; devices, tools, technologies, processes)*
Apply	Apply/Use… • Engineering only • Engineering & at least one life science • Engineering & at least one physical science • Engineering & at least one life science & at least one physical science • At least one life science & one physical science	Student defines BME as the application or use of technical knowledge, principles, or skills *(apply, use)* *(engineering, technology)* *(life science: biology, medicine, biomedical sciences, genetics)* *(physical science: chemistry, physics, math)*
Understand	Understanding or a Combination of… • Engineering only • Engineering & at least one life science • Engineering & at least one physical science • Engineering & at least one life science & at least one physical science • At least one life science & one physical science	Student defines BME in terms of understanding technical knowledge, principles, or skills but does not indicate applying or using them; BME as a combination of certain fields *(understand, combination, <u>no apply or use</u>)* *(engineering, technology)* *(life science: biology, medicine, biomedical sciences, genetics)* *(physical science: chemistry, physics, math)*
Undefined	Undefined	Student indicates that they are not familiar with BME enough to define it *(don't know, not sure, unfamiliar)*

Table 3. Examples of the coding process using definitions from each student population (bold phrases indicate the portions of the definitions identified during in vivo coding)

Example Definition	Quote	Identified Code
1. Introduction to Engineering student	"Biomedical engineering is the process of **designing medical devices** that improve the quality of life for many people."	Design
	"Biomedical engineering is the process of designing medical devices that **improve the quality of life for many people**."	Impact
2. Newly declared BME major	"Biomedical engineering is **the use of engineering principles and methods** to solve and research medical problems."	Apply/Use Engineering Only
	"Biomedical engineering is the use of engineering principles and methods to **solve and research medical problems**."	Impact
3. BME Undergraduate Laboratory student	"BME is **the overlap of engineering & medicine**."	Combination of Engineering & Life Sciences
4. BME Senior Design student	"**Using engineering** to study or create devices that work in the body."	Apply/Use Engineering Only
	"Using engineering to study or **create devices** that work in the body."	Design

Intra-class correlation calculations revealed a high degree of absolute agreement between the coders in their identification of the key features of student definitions (0.97 ICC for the Introduction to Engineering student population and 0.95 for the BME undergraduate laboratory student population). This verification of consistent coding indicates that either coder's results could be used to compare the student groups without significant effect; therefore, the first author's coding results were used for subsequent analysis.

Research Question 2: How do the definitions of students who have not taken a BME core course differ from those who have completed at least one such course?

Figure 1 displays the results of the qualitative coding procedure. Figure 1A indicates the percentage of students within each comparison group whose definition was coded into each category; Figure 1B displays the breakdown of the categories found in each individual student population. Over 60% of the students in the pre-BME group included the potential impact of BME in their definition compared to less than 35% of the within-BME students (Figure 1A). This pattern of decreasing emphasis on solving medical problems or improving health was seen across all four individual student populations moving from Introduction to Engineering students to newly declared BME majors to BME undergraduate laboratory students to BME senior design students (64% to 62% to 40% to 15%, respectively; Figure 1B).

The percentage of students indicating that BME involves the creation or design of something new also decreased from 40% in the pre-BME group to 20% in the within-BME group (Figure 1A). However, with regards to this category, there were considerable differences between the two student populations that were pooled to create the within-BME comparison group (Figure 1B). Of all four individual populations, senior design students had the highest frequency of design-related phrases (close to 50%), while students in the BME laboratory course had the lowest (only 12%).

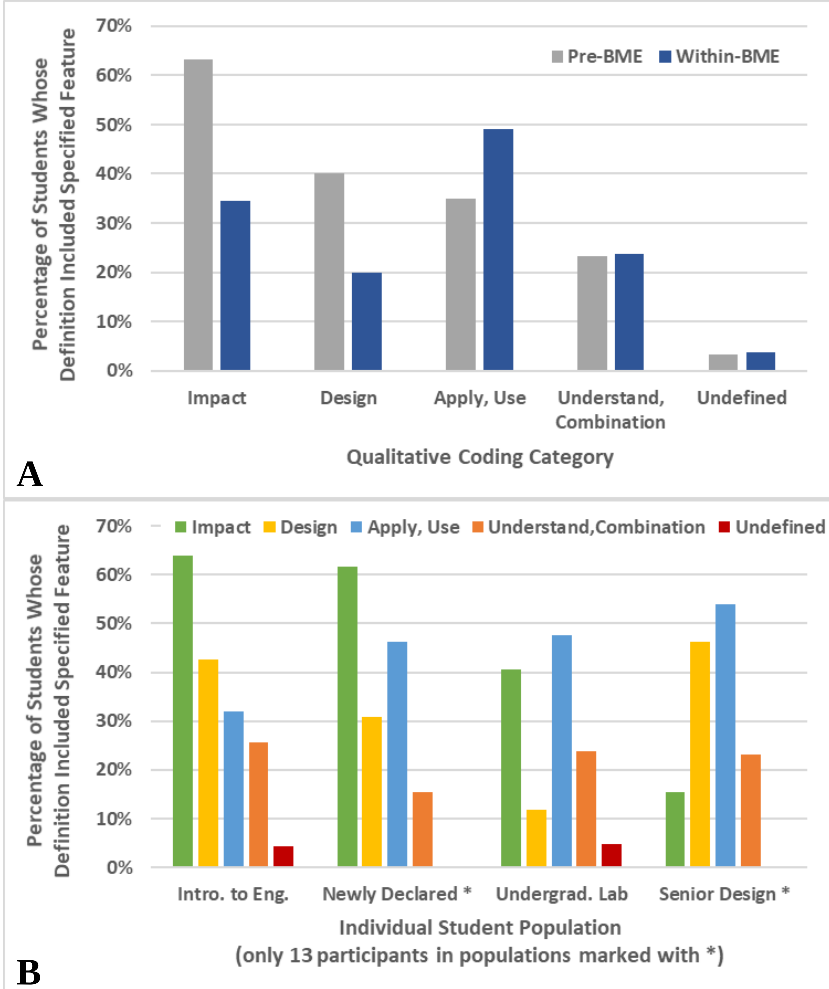

Figure 1. Results of qualitative analysis of student definitions of biomedical engineering

The only category which noticeably increased in frequency from the pre-BME group to the within-BME group was that of describing BME as the application or use of knowledge, principles, or skills (Figure 1A). As with the impact category, this pattern was consistent across all four individual student populations (32%, 46%, 48%, and 54% for the Introduction to Engineering, newly declared BME majors, BME undergraduate laboratory students, and BME senior design students, respectively; Figure 1B). Examining the sub-categories under the main apply/use heading, defining BME as the application of engineering principles alone was the most common in both student groups (23% for pre-BME and 33% for within-BME). Although the counts for the other sub-categories were low, a greater percentage of the within-BME students defined BME as the application of engineering and at least one life or physical science (3% for pre-BME and 13% for within-BME). Conversely, a greater percentage of the pre-BME students excluded engineering altogether when defining BME in terms of application (e.g., "Biomedical engineering is using biology, chemistry and other fields to solve issues pertaining to humanity in terms of medicine, welfare, etc." or "Applying science to solve health issues", 8% for pre-BME and 4% for within-BME). Similar relationships between the two student groups were found when the matching sub-categories of “apply” and “understand” were pooled.

Discussion

Coding is a qualitative research technique which identifies dominant patterns or themes in textual data [20], [25]. In this study, the definitions of BME given by undergraduate students were analyzed as the initial qualitative phase of an exploratory mixed-methods research design [20], [22]. The following section discusses the results using the four ABET BME/bioengineering program-specific curriculum criteria [17] as a framework to examine student perceptions and add to discussions of the development of BME identity during undergraduate education and a shared understanding of BME among the various BME stakeholders. These results will inform the future development and implementation of a quantitative phase of research which will further explore the variables, patterns, and themes presented here.

ABET BME/Bioengineering Curriculum Criteria

The ABET program-specific curriculum criteria for biomedical engineering, bioengineering, or similarly named engineering programs are listed below in their entirety [17].

“The curriculum must prepare graduates with experience in:

a) Applying principles of engineering, biology, human physiology, chemistry, calculus-based physics, mathematics (through differential equations) and statistics;
b) Solving bio/biomedical engineering problems, including those associated with the interaction between living and non-living systems;
c) Analyzing, modeling, designing, and realizing bio/biomedical engineering devices, systems, components, or processes; and
d) Making measurements on and interpreting data from living systems.”

As discussed in the introduction, comparing student and accreditation board perceptions of BME may provide a proxy measure of how well the educational objectives established by ABET are being reflected in the philosophy and teaching of a BME department and internalized by BME students. Perhaps more immediately informative, this comparison may also identify potential areas where student expectations for a BME education are misaligned with those ABET expects for departments. This misalignment likely leads to student frustration and may contribute to decisions to leave a degree program. It should be emphasized that this comparison is not to suggest that the ABET criteria should be established as the authoritative definition of the field, or that the ABET criteria themselves are a perfect articulation of the goals of every BME undergraduate program. However, these four criteria do provide a useful framework for the discussion of undergraduate BME education, as they are supposed points of consistency across all accredited programs. As a final note, each criterion will be presented in the order which allows for the most logical discussion of the study results (as opposed to alphabetically).

b) Solving Bio/Biomedical Engineering Problems

For accreditation purposes, this criterion is often interpreted as the ability of students to solve homework or exam problems in core BME courses. For this report, a broader interpretation of "bio/biomedical" problems as health problems, the solutions of which have a positive effect on society or medicine, allows the criterion to be related to the impact category of student definitions.

Perhaps the most surprising, and initially concerning, result of this study was that students within the BME undergraduate program were less likely to include the potential impact of the field in their definition; only 2 of the 13 BME senior design students mentioned the discipline's ability to address medical challenges, improve healthcare, etc. (the lowest percentage of all four individual student populations). However, when asked about their motivation for pursuing a BME degree, 7 of these same students included statements similar to those coded for impact in the definitions; 3 students specified the desire "help people" as a primary motivation. This suggests that while the potential impact of BME strongly influences students' desire to study it, there is a shift in their perception of the field as they progress through the degree program; an apparent shift from an idealized abstraction of BME to a more realistic expectation of how they themselves may contribute to the field.

Student psychosocial development theory identifies the junior, and especially, senior years as the time college students anticipate their place in the adult world and confirm their "vocational purpose" [29], [30]. As they gain a more accurate understanding of the labor market, they become more focused on what they will be asked to do as a member of the associated workforce [29]–[31]. For BME students, this means focusing on how they will be asked to utilize the knowledge and skills they have acquired, possibly to develop a new product or process. Accordingly, it can be expected that the apply/use category was the most frequently identified for both student populations in the within-BME group, followed closely by the design category in the senior design population. This increase in focus is also evident when comparing responses to the question on jobs/opportunities available to individuals with a BME undergraduate degree. Newly declared BME majors tended to give general responses such as "medicine" and "research", with 3 of the 13 students including phrases similar to "almost anything". The senior design students were much more specific, and pessimistic, about their job prospects, especially in industry. In addition to medical school and graduate school, 6 of the 13 senior design students included work with medical devices or products as a possibility (compared to only 3 of the 13 newly declared students). However, approximately half of the senior design students also included caveats about the difficulty of being hired directly into industry positions (e.g., "industry if you have a ton of experience", "*some* industry positions", "most engineering jobs are available, but our skills are seen as lacking").

a) Applying Principles of Engineering, Life Sciences, and Physical Sciences

An encouraging result of this work is that students within the degree program were more likely to acknowledge the interdisciplinary nature of BME. Defining BME as the use of engineering principles in a medical context was the second- and third-most commonly identified code for pre-BME and within-BME students, respectively. Such definitions reflect the dominant philosophy of early BME education where the discipline was seen as a one-way bridge between traditional engineering techniques and problems in the life sciences [1]. This view of BME ignores the value of using knowledge of the life sciences (e.g., biology, medicine, physiology) and physical sciences (e.g., chemistry, physics, mathematics) in conjugation with engineering knowledge. Within-BME students appear to be more aware of this value based on their more frequent inclusion of at least one life science or physical science in their definitions of BME (pooling "apply" and "understand" results, approximately 20% for pre-BME and 30% for within-BME). The most commonly included science across both student comparison groups was medicine followed closely by biology.

Developing a biological expertise and understanding how to apply both engineering and biological knowledge became emphases in BME education during the 1980s [1]. In this two-way bridge philosophy, engineering and life science principles are often learned independently and then are used to inform each other [1]. This structure of moderate formal integration or synthesis of engineering and the sciences is representative of interdisciplinarity as it has been defined for research purposes [32]–[34]. Recent efforts in BME education have attempted to move to a more integrative philosophy where students "develop true expertise at the interface" of engineering and life sciences [1], [35]. This approach to BME education could be described as transdisciplinary [32]–[35].

c) Analyzing, Modeling, Designing, and Realizing Devices, Systems, Components, or Processes

The "designing" and "realizing" aspects of this ABET criterion are related to the design category identified during coding; this category was noted whenever a student definition of BME included the development or creation of something new. Unsurprisingly, students enrolled in the BME senior design course were the most likely to include design-related phrases in their definitions (46%). This may be due to an increased focus on the tangible tasks related to being a practicing biomedical engineer (as discussed under heading b above), but also may be a by-product of writing the definition in an environment where there is an expectation of designing a device or process. A similarly high percentage of Introduction to Engineering students included design-related phrases in their definition of BME (43%). This is likely a result of the same environmental factor described for the senior design students. All Introduction to Engineering courses are structured around an open-ended design problem that students address in teams over the course of the semester. For the biotechnology-focused course, teams of 3-5 students were tasked with designing a novel diagnostic tool under the guidance of a clinician from the university medical school. The details of this design task were presented to the students in the class period immediately prior to that in which they were asked to write their definition of BME.

Similar to other universities, the current model of the Introduction to Engineering course was developed in the 1990s with a primary goal of introducing first-year engineering students to basic design principles and methods [12], [36], [37]. However, there have been recent calls to incorporate design experiences in the engineering curriculum beyond first-year and senior capstone courses [37]–[39]. This year's Biomedical Engineering Division's call for papers even included "design projects outside of the 1st year and senior capstone courses" as an "emerging topic of particular interest". The BME design sequence at the institution studied includes three design-related courses in addition to the Introduction to Engineering and senior design courses. The second course in this design sequence is the undergraduate laboratory course, but the design-related task was not introduced in detail until after collection of student definitions. Since this student population was the furthest removed from a design-related course assignment, it follows that they would have the lowest frequency of design-related phrases in their definition of BME (12%).

The coding scheme utilized in this study did not explicitly capture the "analysis" and "modeling" aspects of this ABET criterion because they do not necessitate the design or creation of something new. As these terms lend themselves easily to research efforts in BME (e.g., proteomics analysis or cardiovascular disease modeling), exploring the degree to which undergraduate students are cognizant of these aspects of the field may yield important insights into a student's choice to attend graduate school or pursue a research-based career.

d) Making Measurements on and Interpreting Data from Living Systems

This was the only criterion for which an analog was not identified in the student-provided definitions of BME. It represents an important differentiation from all other ABET-accredited engineering disciplines since work with "living systems" is mentioned only in the program-specific ABET criteria for BME/bioengineering [17]. However, it is unclear to the authors how this criterion could be concisely incorporated into a definition of the field. In fact, of the prevailing organizational definitions of BME discussed below, only the lengthy definition given by the Whitaker Foundation includes mention of understanding living systems. It may be that students assume this as a requisite step in addressing health challenges or designing a biomedical device meant to work in or with a "living system", but this warrants additional study.

Limitations

The main limitation of this study is that the data were collected from a relatively small number of students (115) all enrolled at a single institution (large R1 public university). Comparisons of individual student populations were further weakened by the small number of newly declared and senior design students included. Therefore, the results are not likely a reflection of all other BME programs or the BME educational community at large. As stated in the introduction, one goal of this study is to encourage other BME departments to complete similar work and report their findings to gain greater insight into student perceptions of the field. As these perceptions are relevant to recruitment/retention and the development of a coherent field identity, the authors believe broader investigation to be a worthwhile undertaking.

A secondary limitation of the data analyzed for this study is the possibility that the context or setting of data collection influenced students' responses. For the three student populations tied to a specific course, the primary instructor of the course asked students to handwrite their responses while in class; this may have led to students, consciously or not, interpreting the request as associated with course itself, resulting in biased responses. This limitation can be avoided in future data collection efforts by having a person external to coursework administer the surveys (ideally to all students at the same time point in their studies, not just in specific courses).

Conclusions and Future Work

Based on the results of this study, students near the end of their BME undergraduate education are less likely to perceive BME in terms of its potential impact on society. This may be due to an increased awareness of how the student as an individual will be asked to contribute to the field as he or she nears graduation. Students within the degree program also appear to have a greater appreciation for BME as an interdisciplinary field with medicine and biology being the two most commonly included non-engineering disciplines. Finally, asking students to perform a design-related task as part of their coursework may encourage the perception of BME in terms of development or creation of new devices or processes.

As future work, the authors plan to expand collection of qualitative data to additional students within the degree program and hopefully to students at other institutions. Measures of interest for future study include how individual student definitions change over time (including over the course of a single semester) and how the results from programs with a dedicated "Introduction to Biomedical Engineering" course compare to those which do not (such as ours). Additionally, the insights gained from this qualitative analysis will be used to develop a quantitative methodology for testing the conclusions in previous paragraph and exploring the relationships between a student's definition of BME, their motivation to study BME, their degree expectations, and their career attitudes and goals. For example, the authors are interested in understanding if certain features of a student's definition of BME, such as the inclusion of an impact phrase, are associated with a particular intended career path, such as medical school, or with their expectancy-related and value-related beliefs [40].

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Appendix: Analysis of Organizational Definitions of BME

An interesting extension of this study was the analysis of BME or bioengineering definitions given by the prevailing organizations of the field, namely the Biomedical Engineering Society, the National Institutes of Health, and the Whitaker Foundation.

The Biomedical Engineering Society (BMES) web site provides two slightly different definitions of BME through descriptions of what a biomedical engineer does. A PowerPoint entitled "What is Biomedical Engineering and BMES?" linked to on the *About* page [41] provides the first definition, and the *FAQ's About BME* page [42] provides a second, slightly more expanded, definition (for both definitions, bold phrases indicate those coded by the first author).

> "A biomedical engineer **uses traditional engineering expertise** to analyze and **solve problems** in biology and medicine, **providing an overall enhancement of health care**."

> "Biomedical engineers **bridge the medical and engineering** disciplines **providing an overall enhancement of health care**. Biomedical engineers **design and build innovative devices** (artificial limbs and organs, new-generation imaging machines, advanced prosthetics and more) **and improve processes** for genomic testing, or making and administering drugs."

Both definitions include the same impact-related phrase, but only the expanded definition includes any design-related phrases. Although from a 2017 presentation, the first definition is similar to the one-way bridge philosophy of early BME education; under this philosophy the focus is on applying engineering knowledge to the medical field, but not necessarily on developing or applying medical or biological knowledge. The second definition is more reminiscent of the contemporary two-way bridge philosophy in which there is an exchange of knowledge between engineering and the life-sciences, which is more reflective of interdisciplinarity.

The National Institutes of Health (NIH) also provides two slightly different definitions of bioengineering. The U.S. National Library of Medicine [43] provides the first definition while the National Institute of Biomedical Imaging and Bioengineering (NIBIB) [44] provides the second (as above, the bold phrases are those identified as supporting a coding category).

> "The **application of experimental and analytical techniques based on the engineering sciences** to the **development of biologics, materials, devices, implants, processes and systems** that advance biology and medicine and **improve medical practice and health care**."

> "The **application of concepts and methods of engineering, biology, medicine, physiology, physics, materials science, chemistry, mathematics and computer sciences** to **develop methods and technologies** to **solve health problems in humans**."

These definitions of bioengineering are similar in many ways; they both include impact-related and design-related phrases and are application based. However, similarly to the first BMES definition, the Library of Medicine definition mentions only the application of engineering-based techniques. Conversely, the NIBIB definition provides the most exhaustive list of disciplines whose principles and methods are applied, including both life sciences and physical sciences.

The Whitaker Foundation definition of BME (as provided in other publications [2], [5], [9]) is quite detailed compared to those of the other organizations and the students of this study. The main body of the definition is as follows with the bold phrases indicating those coded by the first author:

> "Biomedical engineering is a discipline that **advances knowledge in engineering, biology and medicine**, and **improves human health** through cross-disciplinary **activities that integrate the engineering sciences with the biomedical sciences and clinical practice.**"

Subsequent parts of the definition discuss the importance of acquiring knowledge and understanding of living systems and the development of new devices or systems that improve medical practice and healthcare. The definition formulated by the Whitaker Foundation is similar in wording to that of the NIH. This definition addresses many of the themes identified in this work. Improving human health and medical practice describes the impact of BME; the development of new devices or systems describes design in BME; and activities that integrate engineering sciences with biomedical sciences suggest the application of both engineering and life science principles. The emphasis on integration suggests a more transdisciplinary view of BME which is the current trend for BME education [1].