



Similarities and Differences in Undergraduate Biomedical Engineering Curricula in the United States

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Abstract

Employers, textbook publishers, and existing and emerging educational programs in biomedical engineering and bioengineering continue to be interested in the degree to which the undergraduate curricula of degree granting programs are similar for undergraduates in these fields, and what the similarities are. Several years ago, the VaNTH Engineering Research Center in Bioengineering Educational Technologies compiled information about required courses at 40 of the 43 programs that were ABET-accredited in bioengineering or biomedical engineering at the end of 2004, as well as 31 programs that were not accredited at that time. While these data have been presented in several forums, there has not been a publication on this topic. In the interest of providing data that can be used by different constituencies, as well as a snapshot of the curriculum at a particular point to which changes can be compared, the data from that project are presented here in full. The results from the 2004 sample concerned courses beyond freshman math, physics and chemistry, which tend to be common across engineering majors, to focus on the courses required specifically for the biomedical engineering degree. Mechanics, physiology and design were the subjects required most frequently, at 90% or more of the accredited programs. Other subjects required by 75% or more of the accredited programs were other areas of biology, circuit analysis, computing, statistics, materials, and instrumentation. Several more topics were required by more than half of the programs. There was more variation in the amount of curricular time devoted to different subjects than in the topics that were required. In comparing accredited and non-accredited programs, mechanics, thermodynamics, and materials were required more frequently at accredited programs, while computing and organic chemistry were required by a larger percentage of the non-accredited programs. Normalizing all programs to a credit-hour basis showed that beyond required courses, the median number of credit hours left for specialization or elective courses was 12, and this did not differ between accredited and non-accredited programs. Overall these results showed a high degree of similarity in the required courses across all biomedical engineering programs. The 2013 requirements at sixteen of the programs assessed earlier have been evaluated to determine shifts in the curriculum. While there have been changes in individual programs, the summary statistics reveal few overall shifts in the courses required, reinforcing the relevance of the larger 2004 dataset, and indicating stability in the BME curriculum.

Introduction

As of October, 2013, there were 87 universities with ABET-accredited undergraduate programs in biomedical engineering and bioengineering in the US. Ten years earlier, in 2003, there were just 37 accredited undergraduate programs, but many of the programs that are now accredited had been initiated. The dates when programs were first accredited are available from ABET [1]. The earliest accreditations in biomedical engineering were awarded in 1972 to Duke University and Rensselaer Polytechnic.

For several reasons, we have been interested in characterizing the required curriculum for undergraduates in biomedical engineering at institutions across the United States. Employers, textbook publishers, and emerging educational programs in biomedical engineering and

bioengineering can all benefit from information on the degree to which the undergraduate curricula of degree granting programs share common features. The earliest programs built their initial curricula largely with courses that were available from departments that pre-existed biomedical engineering, and supplemented these with few specific biomedical engineering courses. However, as we will show, a body of required courses has evolved that has great similarity across the country, while still allowing room for elective courses that give the graduates of different programs unique combinations of skills and experiences.

Most of the data presented here comes from an analysis of the courses required at 40 of the 43 programs that were accredited at the end of 2004. At the same time, we also studied curricula at 31 non-accredited undergraduate BME programs in order to determine whether these programs were fundamentally different, or might be pointing the way to future changes in all programs. All but four of those 31 programs have now been accredited. For each of the 71 programs, we analyzed what courses were required of all students, and how many credit hours were devoted to different topics. We also evaluated the number of credit hours available for specialization, and identified the most common areas of specialization. This work was carried out under the auspices of the VaNTH (Vanderbilt-Northwestern-Texas-Harvard/MIT) Engineering Research Center (ERC) in Bioengineering Educational Technologies. Portions of this work have previously been reported in an abbreviated form [2], and at conferences, but until the present publication, there was no archival record of this information to inform the BME community, or to serve as a baseline.

In these data, we found that there was a set of courses taken by most biomedical engineering students that could be regarded as a core of material. Recently, we have asked how the findings of that work may have changed. Without the resources of the VaNTH ERC, we were not able to undertake such a complete study again. Instead, to begin to assess the stability and uniformity of the curriculum, we have evaluated 16 programs, eight that were first accredited between 1982 and 1987, and were therefore in our previous accredited sample, and eight that were first accredited between 2007 and 2009 and were in our previous non-accredited sample.

Methods

The primary source of data was a survey of the frequency with which particular courses were *required*, not simply offered. We reviewed the websites of all programs, as well as university catalogs, in order to obtain the complete descriptions. This proved to be somewhat challenging and required the collective experience of the authors to interpret course names and estimate the number of credit hours devoted to each topic. For this project, we counted courses in a list of identifiable categories (for example, see the labels on the ordinate axis in Figure 1), so it is possible that some topics might be undercounted. For instance, statistics might be covered in a laboratory course, rather than in a course called statistics. Further comments on this point are in the Discussion. Universities do not all use semester credit hours, but when necessary we converted a university's system to a credit hour basis. We did not consider general chemistry, physics, math, or humanities and social sciences, but confined our attention to engineering courses as well as biology and organic chemistry, which are less common topics for other types of engineers.

For the 2004 data sample, 40 of the 43 programs accredited at the end of 2004 were evaluated, along with 31 programs that were not accredited at that time. The three accredited programs that were omitted were Brown University, Worcester Polytechnic Institute (WPI), and Washington University. Brown University's curriculum was not included because the university offered a degree in engineering with a concentration in BME, not a bachelor's degree in BME. WPI's curriculum was not included because of the unique flexibility it allows its students, which could not be mapped without distortion onto the scheme that worked for other programs. Washington University was accredited in October, 2004, and we were not aware of this, so we included it with non-accredited programs. It seems unlikely that moving these data would change any conclusions, so we have not corrected this.

In the more recent review of data, we re-evaluated, using the same scheme, data from eight programs that were first accredited from 1982 to 1987 (Northwestern University, Boston University, the University of Pennsylvania, Marquette University, Johns Hopkins University, the University of Iowa, Arizona State University, and Syracuse University). These were a group accredited sequentially, and we did not omit any programs accredited during that time frame. Eight other programs that were first accredited from 2007 to 2009, and which had been part of our original non-accredited sample (Bucknell University, Illinois Institute of Technology, Pennsylvania State University, University of Southern California, University of Utah, City College of the City University of New York, Clemson University, and Rice University). There were other universities accredited in that time frame as well, but they had not been in our original sample, so we could not use them to investigate changes. By choosing a modest number of programs with similar accreditation dates, rather than selecting particular programs, we hoped to obtain a reasonably unbiased sample of current practice.

An additional part of the data was derived from the VaNTH Key Content Delphi Study [3-5] For this we used the Zoomerang™ survey tool (www.zoomerang.com) to ask about the prerequisite or corequisite courses in math and physical science that should be required of all undergraduate bioengineers. Respondents could choose one of three responses: "should not be required," "not sure," or "should be required." This part of the survey was administered to half of the total sample of respondents; 25 industry representatives and 42 bioengineering faculty members. The company and institutional affiliations of the respondents were broad. An additional question about the importance of having areas of specialization within BME was asked of a similar group of participants in a second round of the Delphi study. None of these data have been previously reported. While there is no full publication on the Key Content Delphi Study, the data are available at <http://www.nceer.northwestern.edu/VaNTH/index.html>.

Results

Data from the 2004 sample

Accredited Programs in 2004. Figure 1 shows the percentage of accredited programs ($n = 40$) that required one or more courses in each area shown on the ordinate (gray bars) in 2004. If a course was required within a track followed by only some students, it was not counted for that university. A central point is that $\geq 75\%$ of programs required physiology, mechanics, biology, circuits, computing, statistics, materials science, and instrumentation for all of their students; 71% of these programs required a course in transport phenomena. All but two programs also

required at least one definable design course, and the others must have had ample design experiences integrated into their other courses in order to be accredited. Functionally, these

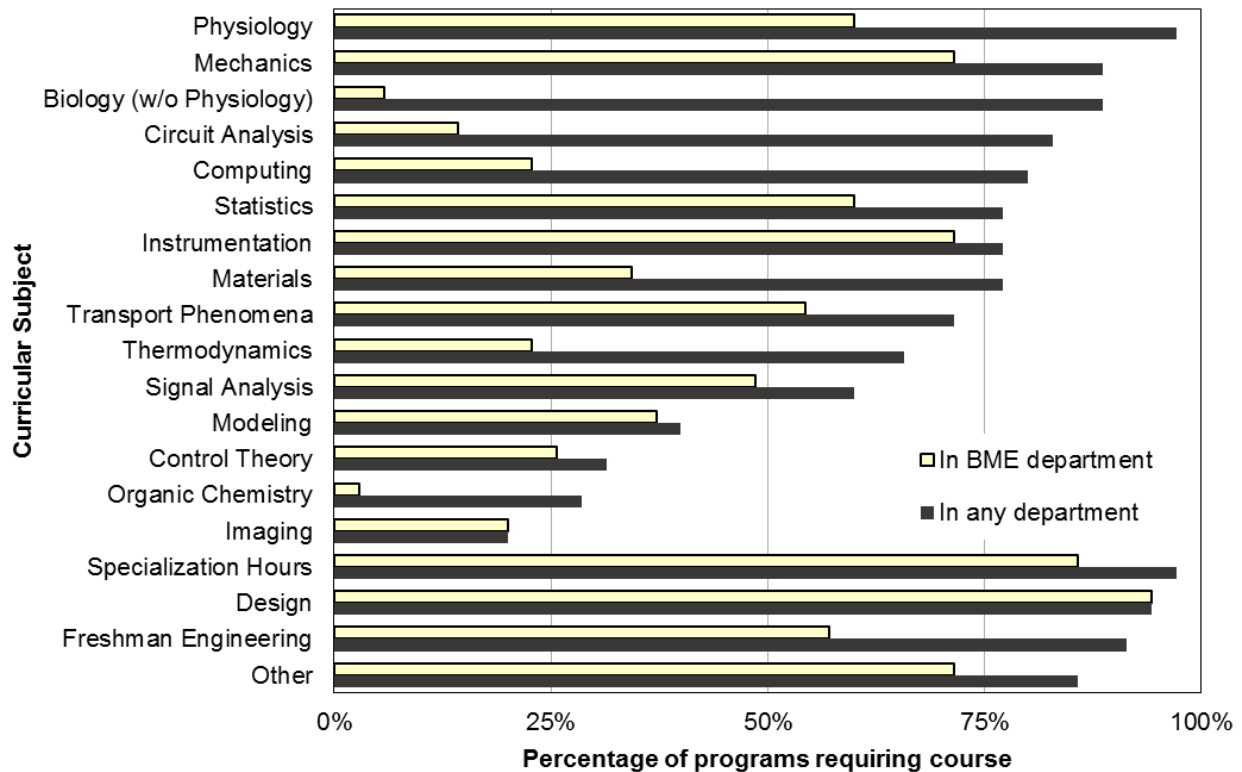


Figure 1. Percentage of undergraduate biomedical engineering programs requiring courses in the topics shown (black bars), and the percentage of programs in which that course was within the BME department (open bars). Data are from 40 of the 43 programs that were ABET-accredited at the end of 2004.

topics comprised the core of bioengineering at the time of analysis. Programs differed in whether each of these courses was taken in the biomedical engineering department or outside of it. The open bars in Figure 1 indicate the percentage of institutions that required that the topic be taken from the BME department. This shows that design, mechanics, physiology and instrumentation were generally taught in BME, while biology, computing, and circuit analysis were not.

The data in Figure 1 do not provide detail on what concepts were covered in any of these courses. In some, for instance a basic materials course or a mechanics course, the appropriate content may be reasonably uniform across different departments. In other cases, the name of the course in Figure 1 may represent material that is less uniform. For example, the term “biology” was used to designate any biology course apart from physiology. We also used the term “transport phenomena” to designate any of fluid mechanics, heat transfer, or mass transfer, but there was some difference in the emphasis on different components of this triad at different schools. Often a part or all of transport was packaged along with material that we have separated out as thermodynamics. The computing category included courses in C++ and in higher level languages such as MATLAB.

Interestingly, when our survey was completed, almost all universities required engineering in the freshman year, with 57% requiring this experience in BME rather than as a general engineering course. The content of these freshman engineering courses is varied, and may include computer skills, engineering problem solving and analytical techniques, introduction to design, introduction to the field of bioengineering, and other topics.

Most universities required a few specific additional engineering courses that did not fit into the categories discussed so far (Figure 1) and these were classified into the category “other.” Courses in this category include ethics, communication (written, oral, and graphical), economics, BME seminars, and professional development. These courses comprised 9 credit hours on average and no program required more than 20 credit hours of “other” courses.

Figure 2 shows the amount of time that each university required in each of the subjects shown in Figure 1. This graph is comprised of data only from those universities that required each of the listed topics. Data were converted to a semester credit hour basis for all universities. The median number of hours for graduation at these universities was 129, with a minimum of 101 and a maximum of 139. A typical semester was then approximately 16 credit hours.

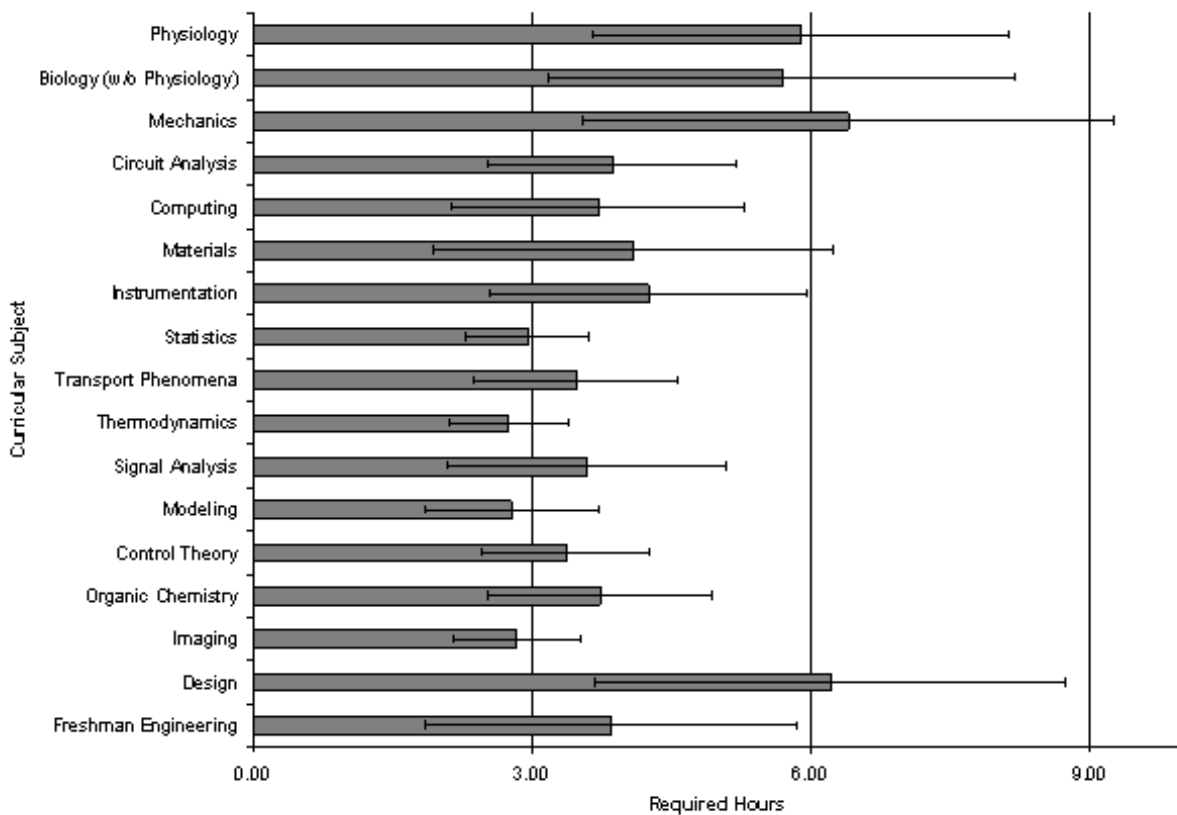


Figure 2: Means and standard deviations of the credit hours required of all majors in accredited bioengineering and biomedical engineering programs in 2004. For this graph, a program was only included if it required the course shown, thereby not distorting the data with schools that did not require the subject. Data from programs on the quarter system were converted, if necessary, to a semester-based credit hour system.

Figure 2 shows that most of the required subjects took 3 to 4 credit hours, or one course, although the standard deviations are rather large. Physiology, mechanics, design and additional biology were the only subjects for which the average was approximately 6 credit hours, or two courses. Of course many of these topics would receive more attention from students with specializations beyond the required core.

Non-accredited programs in 2004. Figure 3 is the corresponding graph to Figure 1 for 2004 data from non-accredited programs. While the ordering of the topics is different, there are only a few noteworthy differences in terms of the percentage of programs that required particular material. These are summarized in Tables 1 and 2. Non-accredited programs required mechanics, thermodynamics, materials, and circuit analysis less frequently, while they required computing and organic chemistry more frequently.

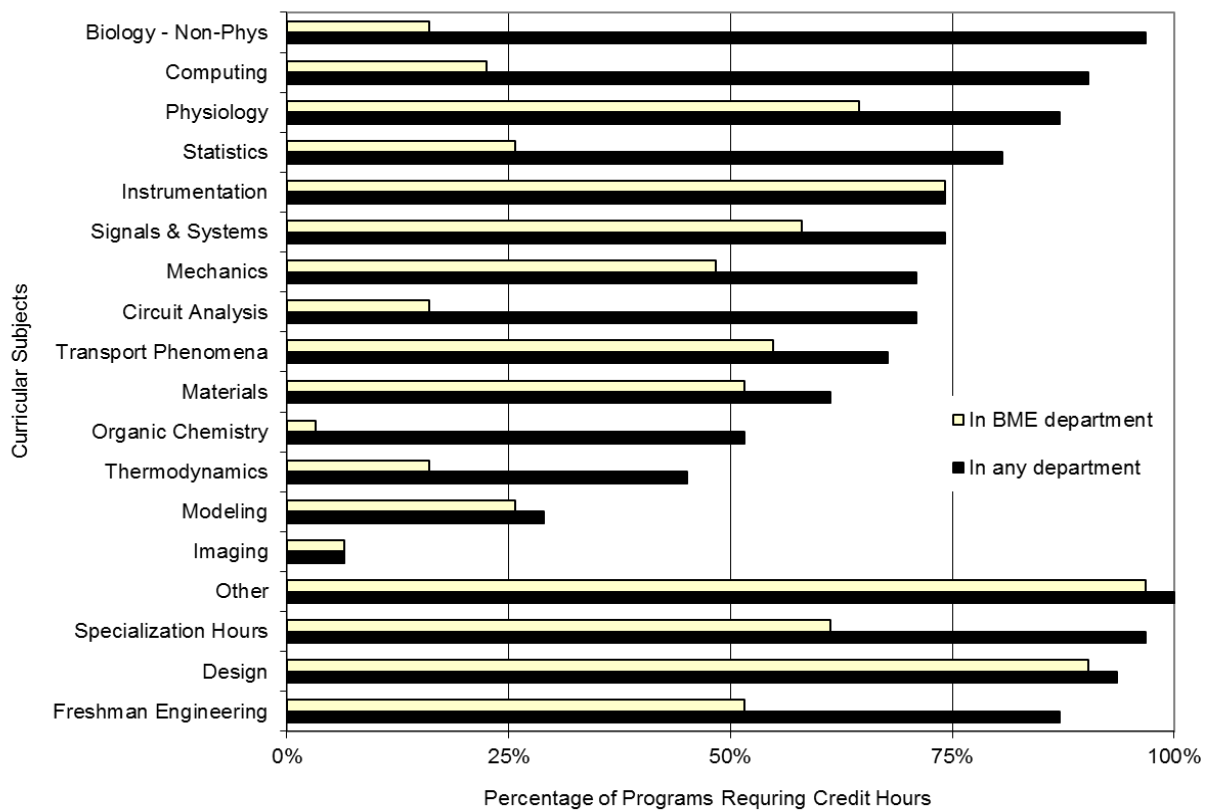


Figure 3. 2004 data from 31 programs that were not accredited in 2004. Format the same as Figure 1.

Table 1: Courses required more frequently at accredited programs in 2004. Differences of less than 5% are not included.

Course Title	Accredited %	Non-Accredited %	Delta (A – N)
Mechanics	93%	71%	22%
Thermodynamics	63%	45%	17%
Materials	78%	61%	16%
Circuit Analysis	83%	71%	12%
Modeling	40%	29%	11%
Physiology	98%	87%	10%
Imaging	15%	6%	9%

Table 2: Courses required more frequently at non-accredited programs in 2004. Differences of less than 5% are not included.

Course Title	Accredited %	Non-Accredited %	Delta (A – N)
Biology	88%	97%	- 9%
Computing	78%	90%	- 13%
Organic Chemistry	28%	52%	- 24%

Electives and Tracks. After accounting for all the courses discussed so far, almost all departments required elective courses in engineering and science (Table 3). In some cases the required electives were left up to the students' discretion, but in other cases a student was required to follow a track of prescribed courses. Although essentially all programs had some elective courses of this type, the number of credit hours varied widely.

Table 3: Credit hours allocated to elective courses.

	Accredited programs	Non-accredited programs
Mean (SD)	12.9 ± 7.3	12.8 ± 6.7
25th percentile	8	8
Median	12	12
75th percentile	16	18

Figure 4 illustrates the most common types of tracks or specializations available to biomedical engineering students at accredited and non-accredited programs, which did not appear to differ substantially, except possibly that a distinct premedical track was available more frequently at non-accredited programs.

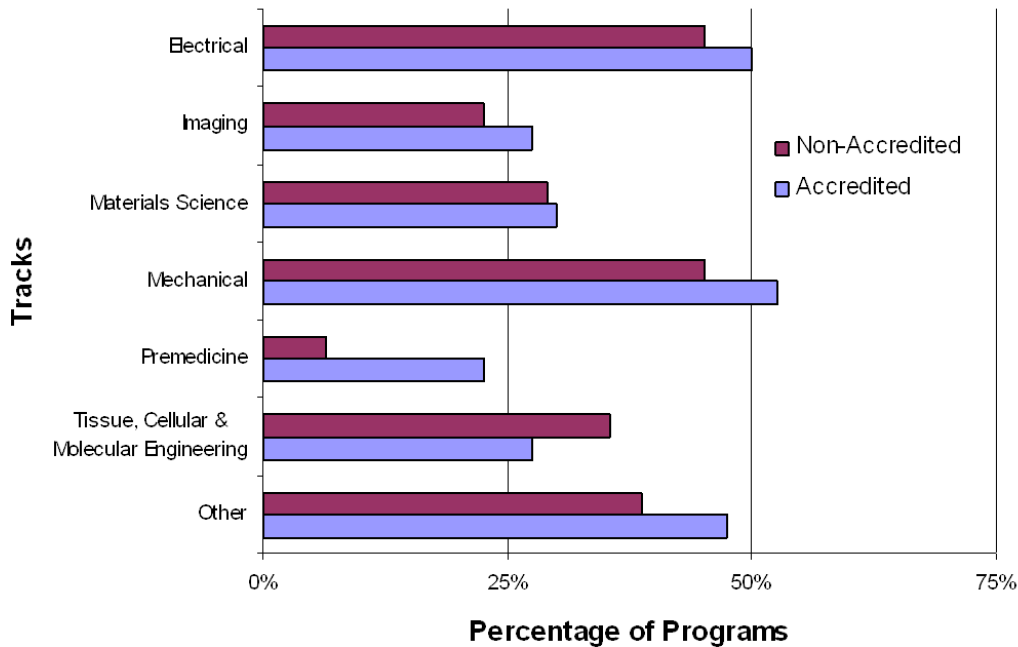


Figure 4: Tracks available to undergraduates in 2004

Data from the 2013 sample

As noted in Methods, current curricula of 16 of the schools previously analyzed were subjected to reanalysis, using current information from websites and catalogs. Eight of these were in our original accredited sample, and eight were in our original non-accredited sample. Both older and newer programs have changed over the time between analyses, but no program went through a major overhaul that changed it completely. The changes included adding and dropping requirements, as well as moving some courses into BME departments and relying on other departments more heavily for others. It was difficult to see major trends in whether the BME department is responsible for a course, except that some BME departments are taking more responsibility for biology courses in addition to physiology. However at some universities, no biology courses are taught within BME. When one combines the data for all 16 programs the overall picture of changes have been quite modest as shown in Figure 5. Design courses are now clearly present at all universities, and there were increases in the percentage of programs requiring transport, statistics, instrumentation, and materials. The only category with a substantial decrease was "other biology," but this is still required at almost 90% of universities. A small difference between the earlier data and the later data is that signals and systems are separate categories in Figure 5, but not in figures 1 and 3. This is somewhat artificial, and combining these categories again shows that for the 16 programs, 75% required this material in 2004, and 81% required it in 2013.

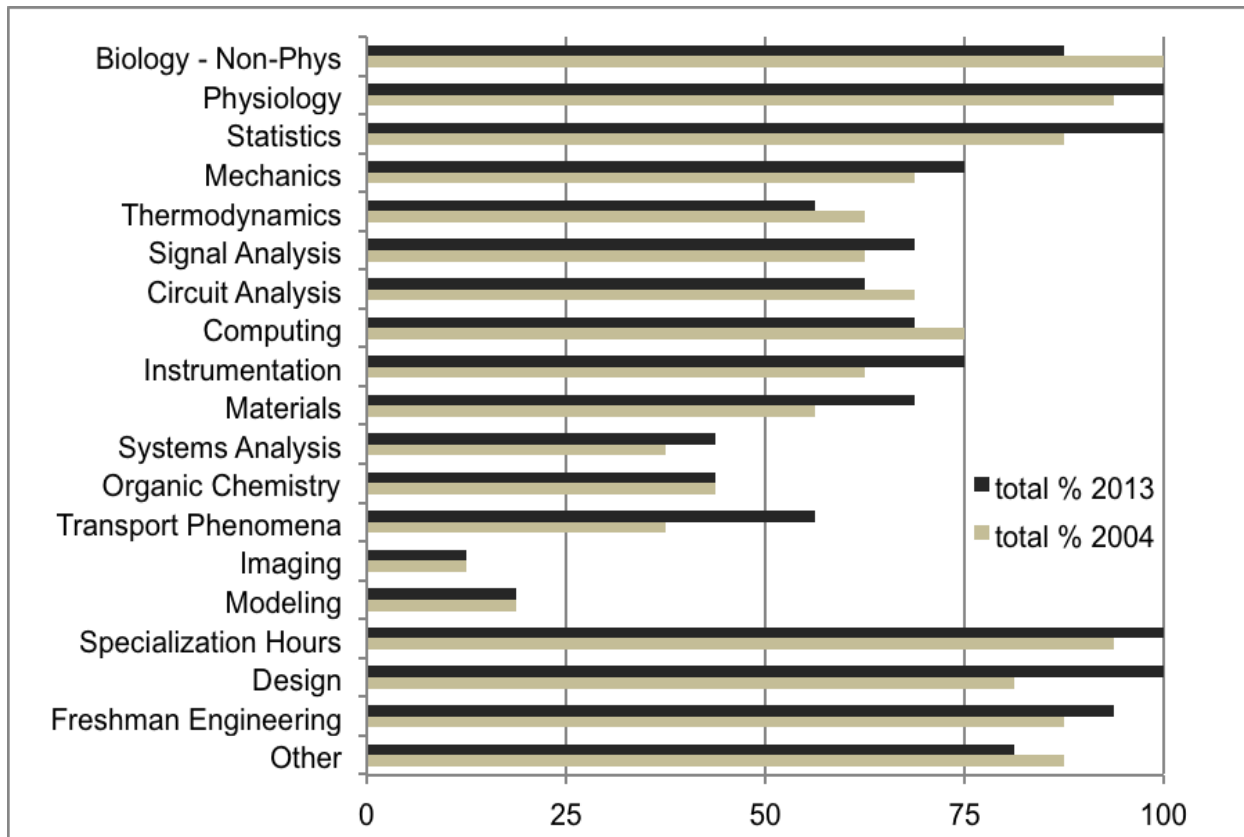


Figure 5. Percentage of programs requiring different topics. These data are from 16 programs for which curriculum was evaluated in both 2004 and 2013. Data shown combine those from universities accredited prior to 1990 and those accredited between 2007 and 2009.

To address the question of whether newer or older programs had changed more, the difference in requirements between 2004 and 2013 was computed for each group of 8 universities. These data are shown in Figure 6. Of the topics that were required by more programs in 2013 (Figure 5), the changes in instrumentation and materials were due to movement in the older programs. Changes in the overall percentages in Figure 5 for transport, statistics, and “other” biology were due to changes in both older and newer programs. Interestingly, across topics, the older and newer programs tended to move in opposite directions in many cases, which perhaps suggests movement toward a common set of “ideals” and kept the percentages in Figure 5 relatively stable.

In terms of changes in credit hours devoted to particular topics, transport was the only subject of note. Transport increased at the older programs requiring transport by an average of 3 credit hours. No other average changes at older or newer programs were this large.

Of the programs reevaluated, eight programs (five of the newer and three of the older), exactly half, rely strongly on tracks for a substantial part of the curriculum. All universities allow some elective courses in engineering and/or science, as noted Table 3, but these eight require that the electives be taken in particular areas. The number of available tracks ranges from two to seven.

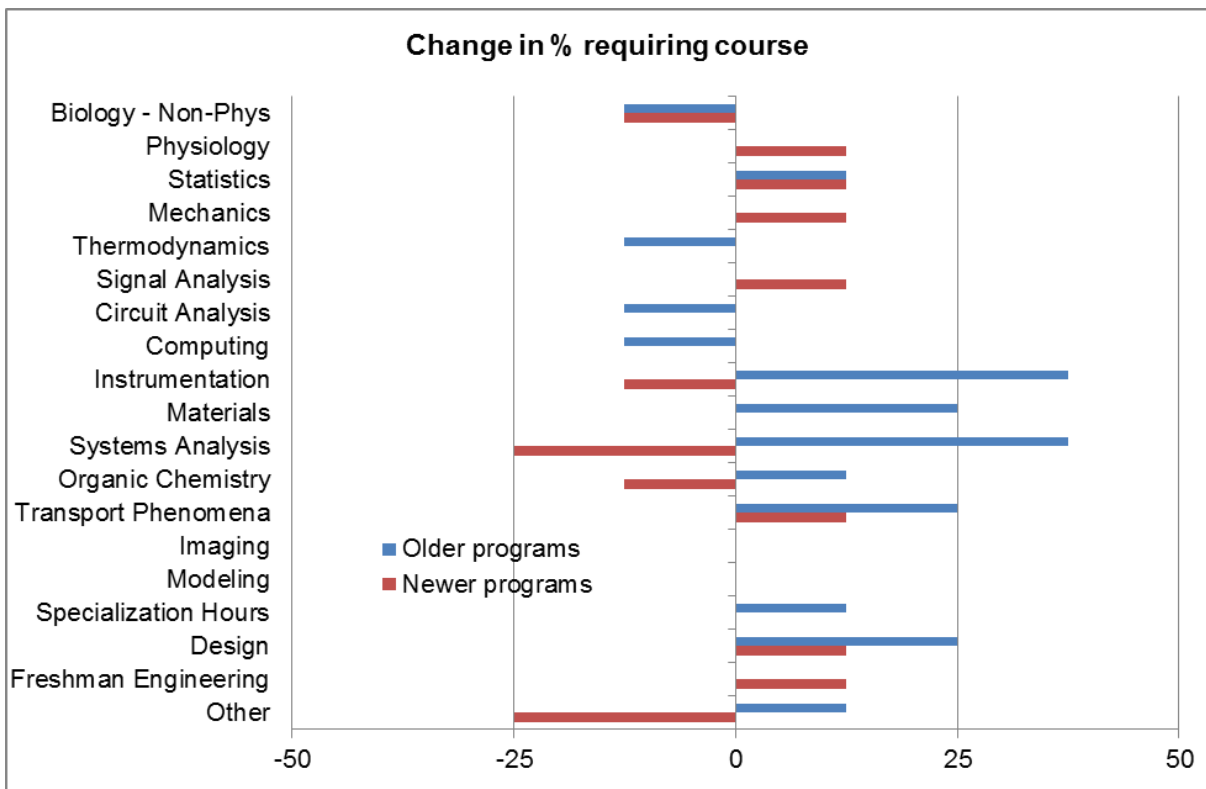


Figure 6. Changes in percentages of programs requiring particular courses. Data separate the older and newer programs, so a change of 25% in the requirement means that 2 of 8 programs changed their requirements for a particular subject. Positive values mean that the subject was required by more programs in 2013 than in 2004.

Opinions from the Delphi Study.

Figure 7 presents data from the Delphi Study, conducted at about the same time as the 2004 curriculum sample, on the opinions of industry and academia on prerequisite or corequisite courses. There was little disagreement about most of the courses in this list, with most math, physics and chemistry courses generating strong support, and a second semester of organic chemistry generally not regarded as being important. Apart from second semester organic chemistry, the prerequisite courses that were rated lowest are vector calculus, a physics course on waves and optics, and the first semester of organic chemistry. A significant number of responses indicated that these were unnecessary or of questionable necessity. The math and physics are generally part of standard sequences for all engineers, so the disagreement is interesting. The first semester of organic chemistry appears to have stronger support from the Delphi study than it did in actual curricula of the 2004 accredited schools, where only 25% required it (Figure 1). Of the sample evaluated in 2004 and 2013, however, it was required at about 45% of the schools (Figure 5).

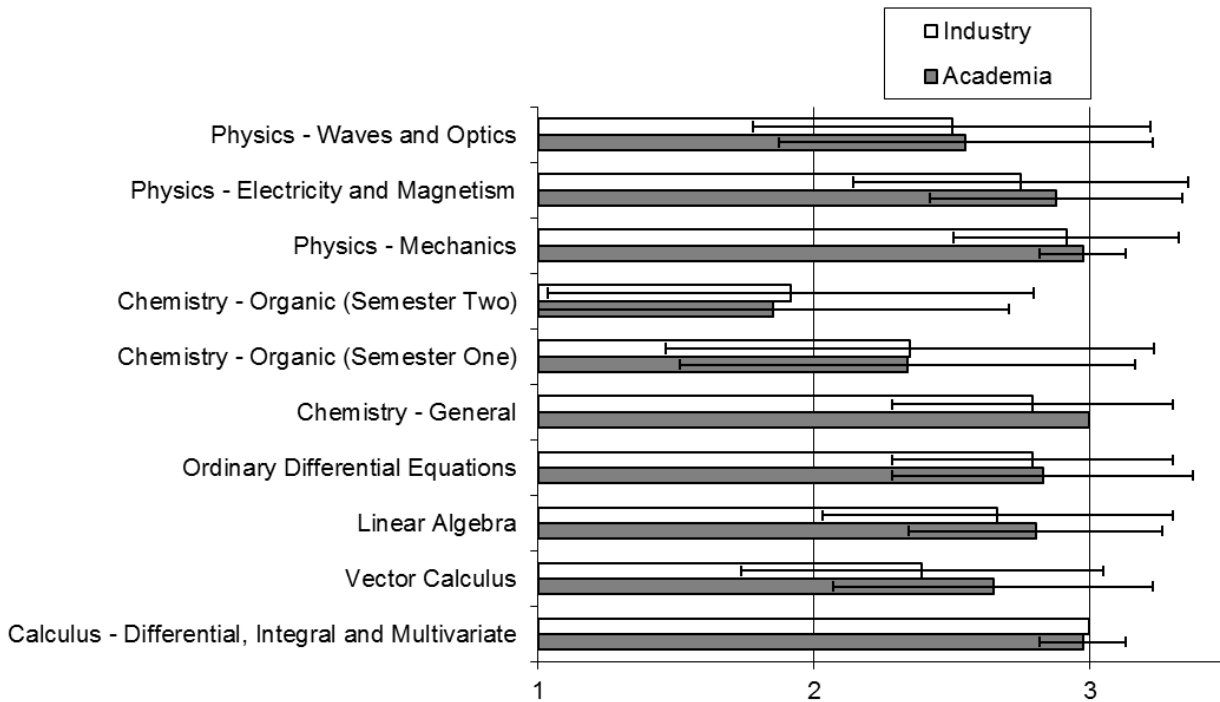


Figure 7. Mean and SD ratings of prerequisite and corequisite courses queried in the 1st round of the VaNTH Key Content Delphi Study. Academic and industrial participants in the survey were asked to rate these courses using a three-point scale: 1, this course should not be required of all undergraduate bioengineers; 2, it is uncertain as to whether this course should be required; 3, this course should be required. Responses from industry are shown by open bars, and those from academia by gray bars. There were no differences ($p \geq 0.05$ in all ten cases) in the mean ratings of these courses by academia and industry.

Another point of some interest is whether tracks are useful in the curriculum. Here opinions varied widely, as shown in Table 4. Many individuals strongly supported the value of tracks, but others did not, reflecting the split within the actual programs.

Table 4. Perceived value of tracks in BME undergraduate curriculum

Option	Participants choosing option
Students should follow a BME track emphasizing depth in a traditional engineering field	23 (29%)
Students should follow a BME track emphasizing depth in a traditional engineering field or in an emerging area (e.g., cellular engineering, systems biology, tissue engineering).	26 (33%)
Students should take advanced bioengineering, guided by recommended sequences, but not formalized as tracks.	17 (22%)
Students should be free to choose advanced courses from bioengineering, other branches of engineering, and biology.	12 (15%)

Discussion

The data presented here show that there is a de facto “core” of material that a BS graduate in BME is likely to know. We tentatively propose that a topic can be considered to be core material if it is required by 75% of programs. By that definition, the core consists of mechanics, physiology and design (required by 90% or more of the accredited programs in 2004) as well as other areas of biology, circuit analysis, computing, statistics, materials, and instrumentation. The modest changes in our re-evaluated sample give us confidence that the more extensive 2004 data are still highly relevant and represent the required BME undergraduate curriculum well. Signals and systems and transport were close to the 75% point in the earlier data, and both showed increases in the smaller sample, suggesting that these topics are close to being core material as well.

Our analysis, at the level of course names and descriptions, does not specify which parts of each topic are covered in these courses, and this is a limitation of our study. However, in most cases we believe that there would be substantial agreement on the most important topics to cover in each course. Other data from the Delphi study [3-5], which are currently available at <http://www.nceer.northwestern.edu>, showed substantial agreement between industry and academia in the most important concepts, rather than courses, for undergraduate biomedical engineers, reinforcing this viewpoint.

In both the older and newer samples of data, a limitation is that the number of programs requiring particular courses is not precise. The values in Figures 1, 3, and 5 are almost certainly underestimates of the topics required at different universities, because we could not categorize all courses exactly. Freshman engineering is the major source of this uncertainty. These courses, required now at almost all universities, generally focus on design, computation using MATLAB or other high level languages, problem solving, and/or modeling. In terms of our graphs, computation and modeling are likely to be the areas that are underestimated most severely, because these are often covered in freshman engineering or other courses. Laboratory courses are another source of error, and may include many topics including statistics, instrumentation, signal analysis, and biology. Characterizing programs rather than student exposure to material potentially underestimates another important element of the data. For programs without tracks, there would be no difference in these measures. For programs in which there are tracks, however, the common set of material is necessarily smaller, but students in particular tracks would know a larger number of the topics. If we could analyze the required material by the fraction of students taking particular courses, rather than the fraction of programs that require courses of everyone, then we believe that the bars for several topics would become longer, particularly for electrical topics, materials, and mechanics. Thus, the number of programs requiring courses probably underestimates the fraction of students who are competent in the areas shown in the graphs.

We reevaluated 16 of 87, or about 20% of currently accredited programs, which is a reasonable sample, but we do not know if all of the conclusions would hold strongly with a larger sample. Overall, the data show a tendency to move toward a common recognized "core" of material that has been relatively stable for at least ten years. It has evolved in the field without

any agency or body attempting to specify such a core. Unfortunately, it is difficult to look back to the early 70's when the first programs were created to see the evolution to this point. However, the data presented here will provide a point of reference for studying the evolution of the undergraduate bioengineering curriculum in the future.

Our analyses have emphasized commonalities across BME, but there is clearly also considerable diversity in BME undergraduate curricula. If we were to investigate certain other branches of engineering, at least five or six topics would be expected to be nearly 100% consistent across programs. The educational diversity in BME results not only from different universities failing to cover the whole "core," as we have defined it, but from students having many elective experiences.

Whether students have more breadth (a large number of common courses) or more depth (tracks) is clearly an unresolved question in BME undergraduate education, with opinions of academia and industry reflecting the diversity that is seen in programs. It will be of interest to revisit this in another ten years, but this is not necessarily a question that needs to be resolved. A remaining question is whether both approaches are equally good for all students, or whether each is best for a subset of students, perhaps having different career goals.

Acknowledgments

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