Undergraduate Biomedical Engineering Curricula – Recommendations from Academia and Industry

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Abstract

The field of biomedical engineering is comprised by a diversity of academic departments and industrial partners. Though there are many examples where this diversity is a significant strength, e.g., developing markets in interdisciplinary areas such as tissue engineering, BioMEMS, etc., the lack of cohesion within the field has become an obstacle to undergraduates seeking positions in industry. Often, recent graduates of biomedical engineering programs (BMEs) are "passed over" by companies in favor of graduates with more traditional engineering degrees, e.g., mechanical, electrical, and chemical. Reasons cited for not hiring BMEs include uncertainty about a biomedical engineer's training as well as a perceived lack of expertise in any particular area of engineering.

Bioengineering domain experts in the VaNTH ERC for Bioengineering Educational Technologies believe that the above hiring practices can be largely attributed to two factors: 1) poor communication between academia and industry, in particular, communicating what skills and training engineering companies desire from their new employees; 2) no clear biomedical engineering "identity" clarifying for industry what skills BMEs possess and what training they have received. In order to resolve these issues we have conducted research in several areas including: 1) mining the Whitaker Foundation database to determine curricular trends across BME departments; 2) interviewing representatives from academia and industry about the above issues; 3) involving more than one hundred academic and industrial representatives in a multi-step Delphi Study to determine and rank the key concepts forming the "core" of an undergraduate biomedical engineering curriculum; 4) proposing a prototype undergraduate BME curriculum and mapping this onto pre-existing BME programs.

From the above efforts we will ultimately make curricular recommendations for the field of biomedical engineering that benefit both industry and academia. The key point here, however, is that our recommendations will be a synthesis of feedback from industry and academia. The domain experts comprising VaNTH are simply collecting and analyzing the information that will result in these recommendations. For academic departments, we expect these recommendations to be integrated with their individual needs. Not all BME departments are alike and we do not wish to make them homogeneous. We do, however, feel that there is a fundamental core to BME that all departments should essentially agree upon. For industry, we hope that these recommendations will help to establish a biomedical engineering "identity" which will facilitate the future industrial hiring of biomedical engineers.

Supported by NSF EEC-9876363

Introduction

Since 1999, the VaNTH (**Va**nderbilt University, **N**orthwestern University, University of **T**exas-Austin, and the joint program in **H**ealth and Science Technology between Harvard and MIT) Engineering Research Center (ERC) has been conducting research in the area of bioengineering education. Combining expertise in learning science, learning technology, assessment and the bioengineering domains, VaNTH researchers have focused on transforming bioengineering education to produce adaptive experts through a collection of educational materials, assessments, and technologies [1]. The underlying pedagogy for these efforts is outlined in the landmark publication, “How People Learn” [2]. In addition, a major effort has been in the area of curriculum development and dissemination [3].

There are approximately forty undergraduate programs in biomedical engineering in the United States (some of which are called “bioengineering”). These programs have developed over almost 40 years, many springing from disparate roots, e.g., mechanical engineering, electrical engineering and chemical engineering. Because of the inherent diversity in these programs, industry has been confused about the capabilities of bioengineers, in many cases limiting the employment of bioengineers with bachelor’s degrees (B.S. or B.E.).

In fact, the undergraduate programs are probably not as different as they first appear, but the way in which they cover material appears to vary because the same concepts may be covered in courses with different names and at different points in the curriculum. Because course names may be misleading, one curricular goal in the VaNTH ERC is to specify those topics that should be required of bioengineers at the level of concepts, rather than specify a list of required courses. For this reason we are working on a Delphi study of bioengineering core content. This study has just completed its first round, providing us with feedback from industry and academia on over 270 concepts excepted from eleven bioengineering domains, physiology, cellular and molecular biology, as well as design. Initially, we have some intriguing results, but a full report on this study will take considerable time (we anticipate conducting at least another two rounds), and we believe that it is valuable to propose a general biomedical engineering curriculum for the purpose of guiding discussion in the community. Other aspects of our philosophy on curricular design are given discussed elsewhere on the VaNTH Curriculum website [1], and in a recent publication [4].

Definitions

In order to specify curriculum, we need to identify the field in which we are trying to provide an education. This requires brief definitions of the terms used to describe biology-related engineering, a topic considered more fully elsewhere [4]. “Biomedical engineering” is often regarded as an application of engineering concepts, mathematics, analysis, design and possibly other methods to unsolved problems in biology and medicine. Until recently, the engineering methods came from roots in the physical sciences and mathematics, and were applied primarily toward systems level biology. More recently, some biomedical engineers have taken a reductionist approach and are working at the cellular and molecular levels. For biomedical engineers, the ultimate goals of gaining a mechanistic cellular or molecular understanding usually relate back to the systems level and a resultant impact on human health.

The term “bioengineering” also often implies a medically related engineering, even though the term could encompass all types of integration of biology with engineering (as previously mentioned, “Biomedical engineering” programs at a number of universities are called “bioengineering”). This is consistent with the way that NIH defined bioengineering in 1997:

> “Bioengineering integrates physical, chemical, mathematical, and computational sciences and engineering principles to study biology, medicine, behavior, and health. It advances fundamental concepts; creates knowledge from the molecular to the organ systems levels; and develops innovative biologics, materials, processes, implants, devices, and informatics approaches for the prevention, diagnosis, and treatment of disease, for patient rehabilitation, and for improving health (NIH Working Definition of Bioengineering - July 24, 1997).” [5]

Note that this definition used the word "biology," but all the examples are pertinent to human health, and the tacit understanding is that bioengineers deal with aspects of animal biology that will eventually give some insight into human health and disease.

Until recently, there has been little confusion about the terms bioengineering and biomedical engineering, because they were essentially synonymous. However, it is possible that in the future the term bioengineering will be used to describe a field that need not have its applications in medicine, and it is already used in this context at a few universities. More generally, however, the non-medical bio-related engineering programs are called "biological engineering" or some variant of that, and have arisen as transformations of agricultural engineering or biological resource engineering programs. Both biological engineering (www.ibeweb.org) and biomedical engineering are currently attempting to define their core curricula, and it seems likely that these will have a substantial, but not complete, intersection. Here, however, we deal solely with biomedical engineering.

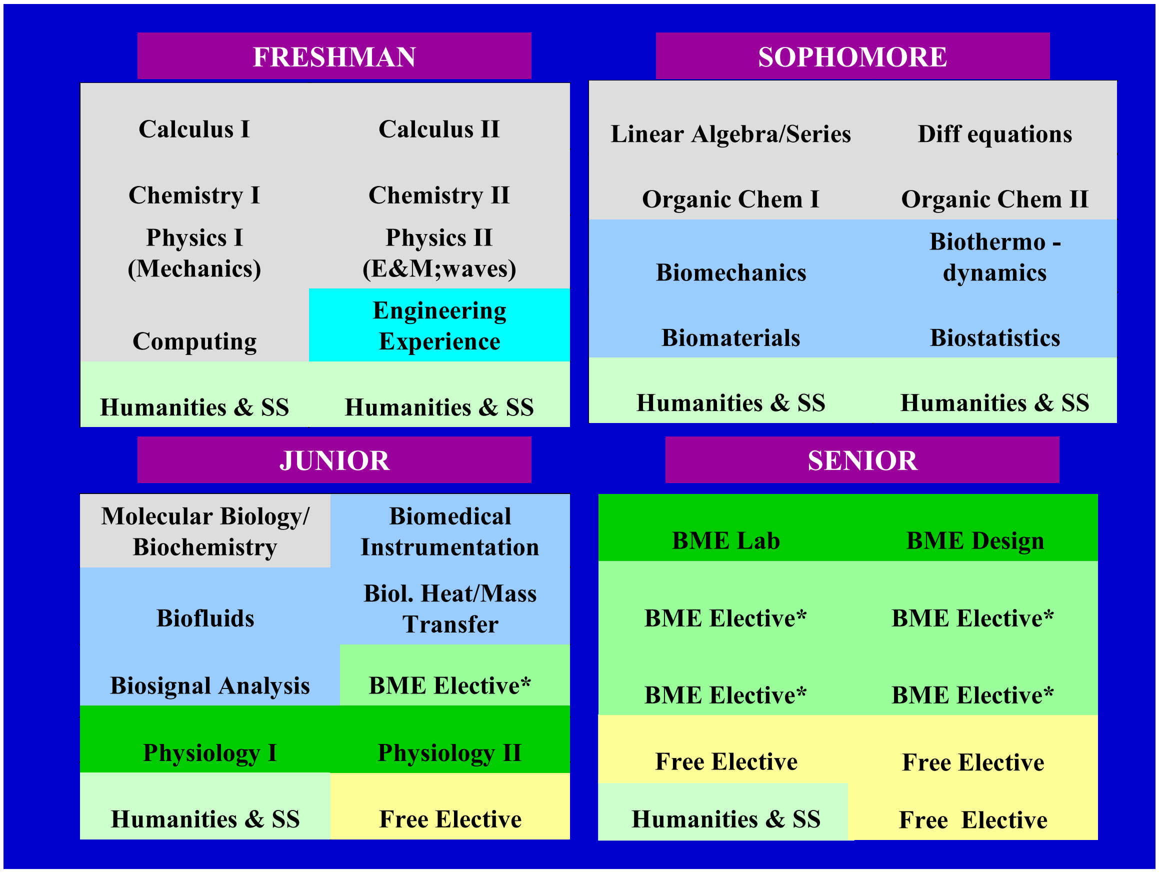
Recommended curriculum

Our recommendations are based on several experiences. First, the VaNTH curriculum project has surveyed the frequency of topics covered across bioengineering programs by mining the database from the first Whitaker Foundation Educational Summit [6]. Second, two of the VaNTH universities have long standing ABET-accredited undergraduate programs and a third has taken a fresh look at biomedical engineering curricula in planning a new program. Third, the VaNTH faculty have spent considerable time discussing curriculum with faculty and industry on a national level over the last several years. Fourth, in generating the Delphi study, we reflected on the key topics that needed to be included in the curriculum. These experiences allow us to propose a number of features of a four-year biomedical engineering curriculum. This is shown in Figure 1 for a university on a semester system.

Science and Math Background

As in other engineering curricula, a considerable part of the first two undergraduate years is occupied with the courses in basic science and math (in gray), including a full year of general chemistry, a full year of physics, two years of math (through ordinary differential equations), and a computing course. At some universities some of these elements will be integrated, so that physics, math and computing may be combined, as they are at Northwestern University in a sequence titled *Engineering Analysis*. We recommend that computing be introduced in the freshman year, but the type of computing is still open to debate. We make no strong recommendation on whether this should be a high level language such as Matlab, or a fundamental computing language like C++ (a quick analysis of the first round of the Delphi Study shows that industry highly values programming skills – a preference for programming environment is yet to be determined). There is an opinion that graduates going into the medical device field may need C++ in order to program controls for such devices.

The basic science portion of the curriculum also includes organic chemistry and biology. As shown (see Figure 1), the curriculum includes a full year of organic chemistry and a semester of biology. There is likely to be some debate on whether a full year of organic chemistry is required for all biomedical engineers, but less debate on the need for at least one semester (as an aside, the BME department at NU is divided on this topic. Those teaching biomaterials support two semesters of organic chemistry, whereas others would prefer to substitute BME courses in place of second semester organic chemistry). Similarly, whether one semester of general biology is adequate is likely to be somewhat contentious. One can make arguments for biochemistry, molecular biology, cell biology, and possibly genetics. We assume that these would be taught in courses that included a laboratory component. However, these may not be packaged by the biology department into courses that meet the needs of the biomedical engineering department, leaving BME programs with options that are less than ideal. The problem can be partially resolved by requiring one or more biology courses that cover parts of the spectrum, and by integrating other elements throughout upper level BME courses. For instance, many of the important topics in cell biology can be accommodated rather easily through a physiology course taught later in the curriculum. Integration of other topics can be done through specialization courses. Another reasonable approach may be to require two semesters of biology, but only one semester of organic chemistry.



FRESHMAN

Calculus I	Calculus II
Chemistry I	Chemistry II
Physics I (Mechanics)	Physics II (E&M;waves)
Computing	Engineering Experience
Humanities & SS	Humanities & SS

SOPHOMORE

Linear Algebra/Series	Diff equations
Organic Chem I	Organic Chem II
Biomechanics	Biothermo - dynamics
Biomaterials	Biostatistics
Humanities & SS	Humanities & SS

JUNIOR

Molecular Biology/ Biochemistry	Biomedical Instrumentation
Biofluids	Biol. Heat/Mass Transfer
Biosignal Analysis	BME Elective*
Physiology I	Physiology II
Humanities & SS	Free Elective

SENIOR

BME Lab	BME Design
BME Elective*	BME Elective*
BME Elective*	BME Elective*
Free Elective	Free Elective
Humanities & SS	Free Elective

Figure 1: Recommended biomedical engineering undergraduate curriculum for an eight-semester sequence. *BME electives are chosen from areas such as: Biomechanics, Imaging, Tissue Engineering, Instrumentation, Optics, Computing, Biotechnology, Biomaterials, etc.

Freshman Experience

In the freshman year we have also included a course titled “Engineering Experience” (in turquoise). It is becoming more common to include at least one course that meets some subset of the following objectives: introducing students to the engineering field and to health problems that biomedical engineers may help solve, introducing students to possible educational and career paths, providing an early experience in design, incorporation of speaking and/or technical writing, or covering engineering topics that do not fit elsewhere in the curriculum. All of these allow the incorporation of at least some features of engineering early in the curriculum.

Basic engineering

At the sophomore and junior level, the blue courses represent eight semester courses designed to give a broad engineering base. These cover a wider range than would be needed in most engineering fields. In the past, breadth was considered to be one of the weaknesses of biomedical engineers. However, we see this now as a strength. To oversimplify, industry is essentially of two perspectives: either they agree with the proposition that part of the value of a biomedical engineer is breadth, and place biomedical engineers in roles where this is valuable (such as regulatory affairs, field service, or leadership of diverse teams), or they may not currently employ biomedical engineers at all. In terms of preparation for graduate school and an ability to handle upper level courses across many fields, the breadth is also a strength.

It is worth noting that these courses are very traditional, at least in name. They are not focused on the exciting new research topics in which academic bioengineers are often engaged. This is because we believe that the traditional engineering courses are still necessary for providing a foundation, and because, at least at this time, our view of curriculum is driven by preparation for industry. There are many more jobs in traditional areas than in new fields like tissue engineering. Undergraduates can, of course, focus their specialization courses in newer areas, as long as they recognize that this may put them at a disadvantage in the job market. There has been little attempt to provide a recommended sequence for these courses. In fact, some of these courses may be mixed into the curriculum later than is shown, if they are not prerequisites for students in a particular area of specialization. For instance, a materials course could be taken at the end of senior year by a student focusing on medical instrumentation or biocomputing; however, some sequencing is clearly desirable.

We believe, based on experience, that it is possible to take a biological or medical focus in these courses, and still cover all of the important engineering concepts. Nothing is lost by offering a biomechanics course as opposed to a basic mechanics course. In fact, a considerable amount is gained. First, this allows the course to be organized around challenges and problems that resonate for bioengineering students, presumably increasing their motivation. Second, a bio- approach focuses the course on the scales that are relevant to biology and medicine, which are not necessarily the same as those in courses offered in other departments. The scales for length, force, temperature, fluid flow, current, voltage, etc, are the relevant ones. In addition to differences in scale, the topics within courses are likely to be somewhat different for biomedical engineers. For instance, in fluid mechanics, studying turbulent flow is considerably less important than knowing about laminar flow, and heat transfer is less important that mass transfer. In biomechanics, everything cannot be described as a rigid body.

Having noted the advantage of teaching these courses with a bio- focus, the practical limitations should also be noted. Few biomedical engineering departments have the expertise or personnel to cover all of these courses in addition to teaching upper level undergraduate courses and an entire graduate program. For this reason, we recommend that a department tackle some of the basic engineering courses, and work with sister departments to cover the others.

BME Core

We believe that bioengineering departments do need to teach laboratory, design and physiology courses (in dark green) for biomedical engineers. The recommendation for capstone lab and design courses does not mean that these should be the only laboratory or design experiences, but ABET has recognized the value of a capstone design experience for integrating and reinforcing knowledge gained previously through at least one real-world experience. We fully agree with the need to incorporate design at earlier stages in the BME curriculum, and there are good examples of universities that have successfully introduced some aspects of design in the freshman year. Physiology is strongly recommended because it appears that industry expects biomedical engineers to have this as part of their background, and because this is the part of biology into which engineering concepts fit most neatly. In fact, with a suitable engineering focus, a department can make the case that the physiology courses can be regarded as engineering science, rather than basic science, for ABET purposes.

BME Specialization

This leaves a number of courses (in light green) for specialization. This is the point at which deep integration of biology and engineering can take place, and the students can achieve depth. Areas of specialization will be determined by local opportunities and constraints. These areas can be quite diverse, ranging, for example, from biomechanics to optics to imaging to tissue engineering to bioinformatics. In some areas of specialization, these courses will undoubtedly be outside BME departments. While we do not attempt here to define this part of the curriculum in detail, some examples of specialty courses would be in imaging (perhaps several courses), biomedical optics, cellular bioengineering, tissue engineering, biotechnology, bioMEMS, bioelectricity, biomedical computing and modeling, and biosystems analysis. In addition, specializations would also include more advanced versions of the core courses.

It is through these specializations that we hope to convince industries that require significant emphasis on typical curricula (instrumentation, imaging, biotechnology) that biomedical engineers can have significant depth, although we are not arguing that BMEs will (or should) displace traditional electrical or mechanical engineers very often.

Limitations

As noted above, we have listed the basic topics that we feel are necessary for biomedical engineers, but listing course names does not specify the topics to be covered. For this reason, the curriculum cannot be filled out fully until the Delphi study has been completed. (The areas in the study are listed in Appendix A, and the full list of topics is posted at www.vanth.org/curriculum.) It may be that the prototype curriculum is too light on electrical engineering topics, control theory, and instrumentation, or too heavy on the chemical and transport side. We may eventually recommend hybrid courses that treat topics in a novel way. It should also be noted that the prototypical curriculum does not exactly match the curriculum at any of the VaNTH schools, but all are comfortable with it, and so are a cross section of representatives from other universities (data not shown).

As we have noted elsewhere [4], content is just one side of curriculum. In addition, there are a set of professional skills, or core competencies, the top levels of which are – engineering and technical skills (diagnosis, planning and modeling, experimental and computational), ethics, communication, project and people management, teamwork, and life long learning. These areas comprise most of the required “a-k outcomes” expected by ABET. Full courses in some of these topics are valuable, but the strategy in VaNTH is to work toward integration of these competencies into content courses. A full list of competencies is posted at www.vanth.org/curriculum, and a complementary effort to identify these topics, most of which are not unique to bioengineering, has been made in the CDIO (Conceive, Design, Implement, Operate) project, which was initiated at MIT, but like VaNTH, has many university participants (www.cdio.org). That list, which attempts to identify not only the topics, but also proficiencies to be expected of BS or BE graduates, is titled the CDIO Syllabus [7].

This curriculum discussed here also ignores pedagogy, focusing on “what” rather than “how.” Elsewhere on the VaNTH website (www.vanth.org) are many suggestions and reports of research emphasizing the importance of recognizing learning science principles in the design of curriculum.

Further comments

The curriculum outlined here should meet the needs of industry and should also meet ABET requirements. It is also compatible with premed requirements with no additions to the science component. While the curriculum includes only one semester of biology taught by the biology department, we have found that medical schools can often be convinced that biomedical engineers do not need a full year of biology that is called "biology," because they have physiology and a great deal of additional bio-related laboratory experience.

Two important ways to introduce industrial practice into the curriculum are through internships and design problems suggested by industry. VaNTH has exerted considerable effort in internships and design. The internship program is based on extensive contacts with specific industries. Industrial partners can contribute materially to the design efforts. A third possibility, of course, is a co-operative engineering experience that can be layered on top of this curriculum by adding one more year.

The curriculum assumes that the student has no AP credit coming in, but of course more flexibility and opportunities become available if the student has AP credit. Even if the curriculum is followed exactly, students should have opportunities for research experience by using some of their free electives.

VaNTH has devoted a great deal of its energy to developing curricular materials in the green and blue areas of Figure 1, and additional effort to what are likely to be the first level courses in important areas of specialization such as bio-optics and biotechnology. In fact, VaNTH now has some ongoing efforts in all of the blue areas, and will shortly have full courses available in many of them.

Acknowledgements

We thank Drs. Tom Harris, Julie Greenberg and Cynthia Paschal for their comments on this work.

References

[1] http://www.vanth.org/.

[2] Bransford JD, Brown AL, Cocking RR, eds. 1999. *How People Learn: Brain, Mind, Experience, and School.* Washington, DC: Natl. Acad. 374 pp.

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[4] Linsenmeier, R.A. (2003) "What Makes a Biomedical Engineer? Defining the Undergraduate Biomedical Engineering Curriculum". IEEE Engineering in Medicine and Biology, 22(4) 32-38.

[5] http://www.becon.nih.gov/becon.htm, accessed on March 1, 2003.

[6] Whitaker Foundation (2000) Biomedical Engineering Educational Summit Meeting. http://summit.whitaker.org/.

[7] The CDIO syllabus is available in several formats at: http://www.cdio.org/cdio_syllabus_rept/syllabus_index.html.

Appendix A - Areas covered in the VaNTH Delphi Study of Key Topics – First Iteration

In parentheses is the number of questions followed by the number of topics in the first iteration of the study. The full list is posted at www.vanth.org/curriculum.

1. General Engineering Skills (3/9)
2. Mathematical Concepts (4/15)
3. Science Pre- and Co-requisites (4/8)
4. Design (3/27)
5. Biosignal and Systems Analysis (3/18)
6. Bioinstrumentation (3/12)
7. Bio-Optics and Photonics (3/9)
8. Medical Imaging (3/6)
9. Biomechanics (3/9)
10. Biothermodynamics (3/17)
11. Fluid Mechanics (3/11)
12. Heat and Mass Transfer (4/15)
13. Biomaterials (3/9)
14. Biotechnology (1/1)
15. Bioinformatics (3/9)
16. Physiology (20/50)
17. Biology (9/40)