Defining the Undergraduate Biomedical Engineering Curriculum

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Abstract

Undergraduate degrees have been offered in biomedical engineering for more than 30 years, and industrial opportunities are expanding. Opportunities may be limited, however, because segments of industry are uncertain about the characteristics of a biomedical engineer. In response to this, and to assist new programs, the Curriculum Project of the VaNTH (Vanderbilt-Northwestern-Texas-Harvard/MIT) Engineering Research Center in Bioengineering Educational Technologies seeks to determine the key topics that should be part of the curriculum for all undergraduate biomedical engineers.

Key Words: biomedical engineering curriculum, core curriculum, undergraduate education

This article focuses on undergraduate biomedical engineering curriculum, particularly on how to address industrial needs and to what extent a common curriculum can and should exist. It is part review, part description of the current work of the Vanderbilt-Northwestern-Texas-Harvard/MIT Engineering Research Center in Bioengineering Educational Technologies – the VaNTH ERC [1], and part editorial. The editorial offers a snapshot of the continually evolving effort to integrate ideas from many sources for the improvement of curriculum in biomedical engineering. These ideas and recommendations are accessible on the website of the VaNTH Curriculum Project [2]. The term biomedical engineering (BME) denotes a type of engineering with a strongly medical focus. It encompasses programs that are called bioengineering (BE), but which have the same flavor as BME.

The first BME undergraduate degrees were granted less than 40 years ago. Full agreement about the content knowledge needed for a BS in BME does not exist now, and is not likely to exist in the near future. Our recent survey of required curriculum in accredited programs found no courses that were required by all, although courses in biomechanics and systems physiology were quite common. This lack of agreement at the course level does not mean that there is no similarity at the content level, however, and, as explained below, our hypothesis is that it will be possible to achieve consensus about key elements of the biomedical engineering curriculum.

Current Status

During the 1970s, there was a steady growth in the number of programs granting undergraduate degrees, with the number of graduate programs always being larger than the number of undergraduate programs. At many universities, the awarding of degrees preceded the creation of the BE or BME departments. At present there are 24 programs accredited by ABET, with the earliest accreditations being those for the programs at Duke University and the Rensselaer Polytechnic Institute, both in 1972 [3]. A handful of additional programs have existed for a number of years without ABET accreditation, primarily because their educational philosophies do not allow them to meet the ABET criteria. After a lull in the 1980s, the 1990s and early 2000s have seen a rapid increase in the number of bioengineering programs (see Fig. 1), spurred partially by resources made available by the Whitaker Foundation [4]. Other aspects

of the growth of the field are reviewed in [5] and [6]. The number of accredited programs is expected to roughly double in the next few years as new programs graduate their first classes, but growth beyond that is uncertain. The number of graduates in BME is small compared to those in the more established engineering fields. While it is not easy to count the graduates precisely, given the variation in names of the degree, it appears that 1,049 BME BS degrees were awarded in 2000-2001 [7] compared to more than 21,000 in electrical engineering and more than 13,000 in mechanical engineering, the fields with the largest numbers of graduates. Still, BME is often one of the most popular engineering majors at the schools that offer it, including Duke, Johns Hopkins, Northwestern, UC San Diego, and Vanderbilt.

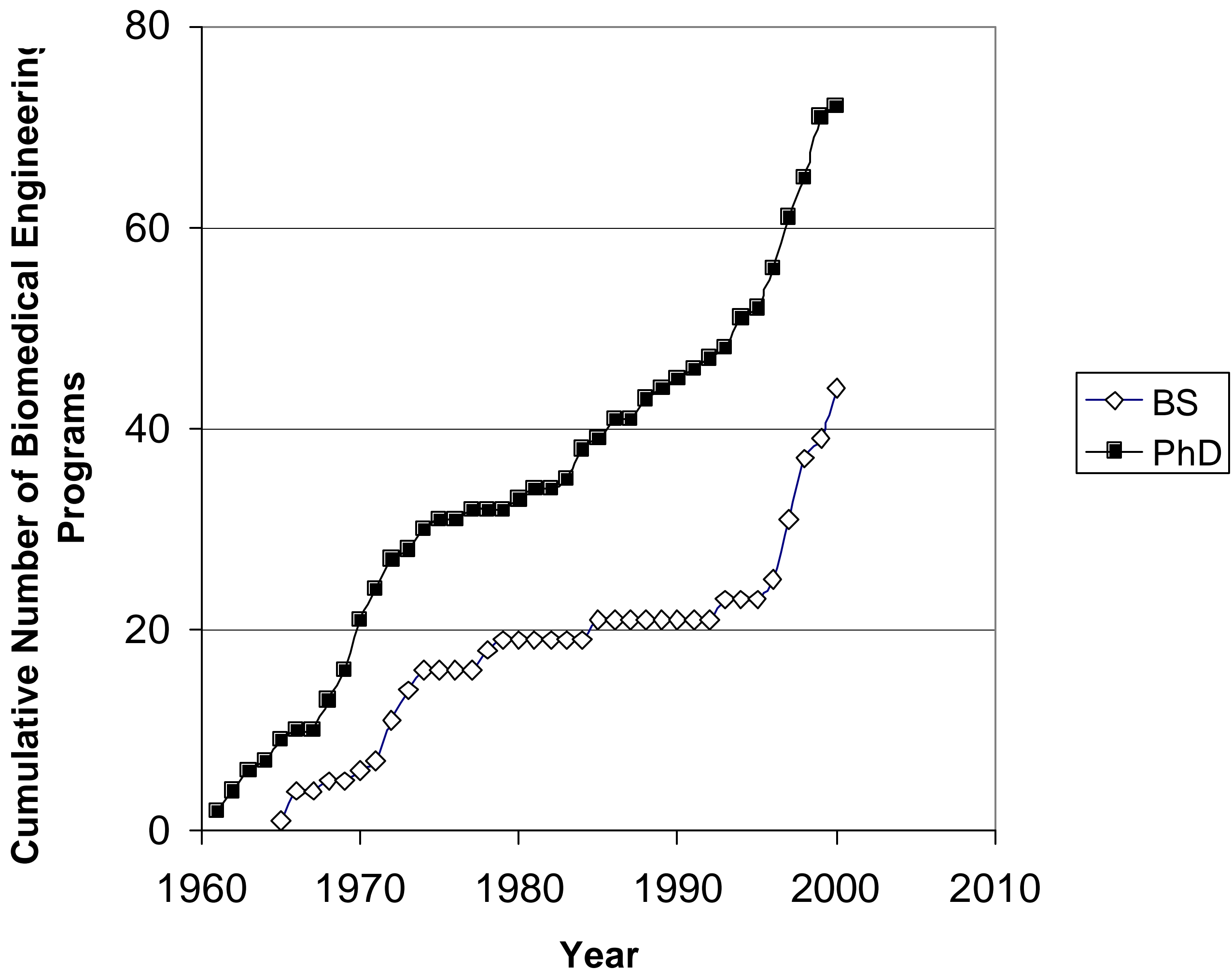

Figure 1. BS and PhD programs in biomedical engineering, compiled from Whitaker Foundation Data, 2000 [5]. Reprinted with permission from the Annual Review of Biomedical Engineering, Volume 4, ©2002 by Annual Reviews, www.annualreviews.org.

Until recently, biomedical engineering was seen by many as a quantitative premedical track, but the number of positions in industry has grown. The change in the focus of graduates at Northwestern is shown in Fig. 2. Seventy percent of BME graduates went to medical school in the early 1990s, but then the number dropped steadily to about 35%. Correspondingly, industrial positions rose from only about 10% to 30% before the economic downturn of 2001-2002 partially reversed these trends. A relatively constant 15% of students have pursued graduate degrees. This distribution of outcomes does not necessarily represent all BME programs, but is not far from the national average. The national picture was obtained in a survey completed by 45% of the members of the Academic Council of the American Institute of Medical and Biological Engineering, representing 445 BS graduates in 2001-2002. Of the graduates who knew their next career step, 21% planned to attend medical school, 36% were pursuing further studies in engineering, and 36% went to industry [8]. In all of these exit surveys, the outcomes for up to 30% of the group are unknown at the time of graduation, but anecdotal evidence suggests that the "unknowns" distribute in about the same proportion as the "knowns" among the most prevalent outcomes of graduate school, medical school and industry. In the AIMBE survey, for instance, about half of the "unknowns" reported that they were "seeking a job," and if they all found a job in industry, then the total fraction going to industry would be 42%

The distribution of graduates has important implications. First, at most universities, BME programs must prepare their graduates for a variety of postgraduate options, and the uncertainty of medical school admission suggests that there should be similar tracks for those intending to enroll in medical school as for those intending to work in industry. Second, the increase in the number of positions in industry for biomedical engineers means that industry is a constituency that should be consulted about the curriculum. Preparing graduates for medical school is straightforward, in terms of curriculum, because the requirements are clearly established. Because none of the required courses are in engineering, biomedical engineering programs are, in a sense, off the hook. Biomedical engineers do well in medical school, and have one of the highest medical school acceptance rates of any major, 57.6% of applicants in the 1999-2000 entering class [9]. Preparing BME graduates for graduate school is largely a question of providing early research training and opportunities, and these generally do not have to be formalized in the coursework. The focus, therefore, should be on preparation for industry, which requires that we address the following questions: What perception does industry have of

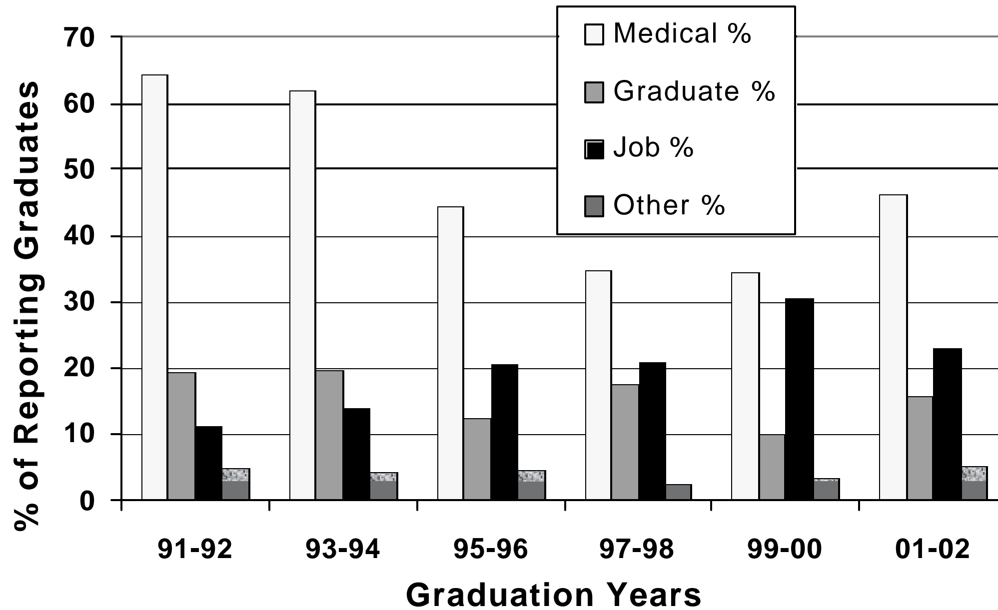

Figure 2. Undergraduate outcomes from the Biomedical Engineering Department at Northwestern University based on senior exit surveys. Over this time the total number of graduates had a generally upward trend from 40 to 60 per year. These data are based on graduates who had a clear path at the time of the survey, and are based on a total that excludes approximately 30% of graduates who did not respond or were uncertain.

biomedical engineers? What are the needs of industry? What niches will biomedical engineers occupy at the BS level? Which industries should we consider in our analysis of needs?

Definitions: Biomedical engineering, bioengineering, and biological engineering

In order to specify curriculum, we need to specify the field in which we are trying to provide an education. Is there a distinct discipline we can call biomedical engineering or is it an interdisciplinary field without a core of its own? This requires comparisons of the definitions of related fields, a digression from our main topic. The discussion here is an expansion of that provided by Harris et al. [5].

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. The Whitaker Foundation uses an expanded definition that is consistent with this:

> "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. It includes: 1) The acquisition of new knowledge and understanding of living systems through the innovative and substantive application of experimental and analytical techniques based on the engineering sciences, and 2) The development of new devices, algorithms, processes and systems that advance biology and medicine and improve medical practice and health care delivery. As used by the foundation, the term "biomedical engineering research" is thus defined in a broad sense: It includes not only the relevant applications of engineering to medicine but also to the basic life sciences." [10]

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 in academia have taken a reductionist approach and are working at the cellular and molecular levels. Molecular and cellular approaches have been comfortably integrated into BME without a change in the biomedical focus of the discipline. 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" often implies a medically related engineering, even though the term could encompass all types of integration of biology with engineering. The longstanding "biomedical engineering" programs at a number of universities, including the University of Pennsylvania, the University of California at San Diego, Arizona State University, and the University of Illinois at Chicago (UIC) are called bioengineering. In 1997, the NIH Bioengineering Definition Committee developed a definition that could have been used for biomedical engineering:

> "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)." [11]

The term bioengineering, meaning biomedical engineering, is used in the title of the National Institute of Biomedical Imaging and Bioengineering, created in 2000, and in the cross-institute NIH Bioengineering Consortium, BECON. Note that the above definitions for both biomedical engineering and bioengineering use the word "biology," but all the examples given are pertinent to human health, and the tacit understanding is that we are dealing 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. It has been noted, however, that the field is evolving from one in which there were a few bridges between the separate fields of biology and engineering to one in which biology and engineering are fully integrated in the curriculum [6]. It is possible that the term bioengineering will be generally recognized as the term describing the more integrated approach, and this would also be completely consistent with the NIH definition. One program that has identified some of the principles that make engineering based on life sciences different from engineering based on physical and chemical sciences is the Bioengineering Department at SUNY Binghamton [12]. The philosophy is that there is a core of ideas essential to living systems that bioengineers will understand and use, but which other engineers typically will not. These revolve around the concepts of self-organization,

self-replication, non-linearity, and emergent properties that arise from the assembly of cells and tissues into complex living systems.

Biomedical engineering is not the only engineering field that relates to biology. Two other branches – really more like trunks – are represented in the two non-biomedical programs supported by the NSF Division of Bioengineering and Environmental Systems. One of these major efforts is devoted to Biochemical Engineering and Biotechnology (BEB). NSF states that its effort in BEB:

> "Advances the knowledge base of basic engineering and scientific principles of bioprocessing at both the molecular level (biomolecular engineering) and the manufacturing scale (bioprocess engineering). Many proposals supported by BEB programs are involved with the development of enabling technologies for production of a wide range of biotechnology products and services by making use of enzymes, mammalian, microbial, plant, and/or insect cells to produce useful biochemicals, pharmaceuticals, cells, cellular components, or cell composites (tissues)." [13]

The core of this is chemical engineering, but one can also see aspects of biomedical engineering in this statement. The second focus at NSF is Environmental Engineering and Technology (EET). Much of this is not biological at all, but the biological aspects are found in the statement that:

> "This program also supports research on innovative biological, chemical, and physical processes used alone or as components of engineered systems to restore the usefulness of polluted land, water, and air resources." [14]

An additional trunk is biological engineering. The Institute for Biological Engineering (IBE) defines this in the following way:

> "Biological Engineering is the biology-based engineering discipline that integrates life sciences with engineering in the advancement and application of fundamental concepts of biological systems from molecular to ecosystem levels." [15]

The type of biological engineering described by IBE originated in departments having a focus on the engineering associated with the agricultural aspects of biology and on biological resource engineering – the use and management of natural products beyond agriculture. The

definition above gives little hint of this, suggesting that this field is undergoing a transformation and becoming broader. One of the authors who has stated a philosophy to direct biological engineering is Arthur Johnson, who has written that biological engineering should be a science-based rather than an applications-based discipline, with broad training in biology and engineering science at the undergraduate level, rather than a focus on applications. The assumption is that most students should go on to graduate degrees where they will choose specific application areas, such as BME, to study in detail. [16,17] While its origins are different, related ideas appear to underlie the new Biological Engineering Division at MIT [18]. If it were stated in one sentence, an MIT definition of biological engineering might look very much like the IBE definition. The philosophy of the new MIT division is that insights and rapid advances in understanding biology at the cellular and molecular levels have set the stage for making biology an additional core science underlying a particular type of engineering. This would add biology to the mathematics, physics and chemistry that now underlie all of engineering. This is similar to the ideas behind bioengineering at Binghamton, but, at MIT, BME is explicitly described as just one application of biological engineering.

These approaches to biological engineering are creating novel programs, and one might call this the "new biological engineering." In many cases, however, the term biological engineering still connotes agricultural and biological resources engineering rather than a broad scope that could include biomedical engineering. This alternate view of biological engineering and biomedical engineering, which sets them as application-oriented equals, is also reasonable. There are common elements among this "traditional" biological engineering and biomedical engineering, thanks to the evolutionary conservation of biological mechanisms at the molecular and cellular levels, but the systems, or assemblies of cells, on which these fields focus are different, and this is likely to keep training in biological engineering and BME separate for some time. Systems level biology is not a simple application of the lower level principles, but involves complexity and emergent properties; learning systems biology takes as much room in the curriculum as molecular biology, and there is not time to learn multiple systems in any detail. Humans are the system that is critical to biomedical engineers, while ecology and plant physiology are more likely to be the province of traditional biological engineers. The fields are also likely to remain distinct because the career paths of biological engineers and biomedical engineers are generally different. Education in all the systems is therefore not only impractical;

it may also be unnecessary. Venturing out onto a limb, one can assert further that education in biochemical engineering, the other major related field, need not cover biology at *any* systems level, because its practitioners study or exploit primarily cellular processes. Perhaps this is what sets the boundary between biochemical engineering and the other fields.

The NSF has charged the VaNTH Engineering Research Center with working on "bioengineering educational technologies," but there are too many complexities to tackle curriculum in all of the biology-related engineering fields at once. Biomedical engineering, bioengineering, biochemical engineering, and biological engineering overlap, but can be distinguished. The term bioengineering was once interchangeable with biomedical engineering, but its meaning may be evolving to describe a new biology-based discipline. The work of VaNTH is primarily in BME at present, but as the foregoing analysis indicates, other biologically related engineering disciplines are on the radar screen. The IBE is undertaking a parallel project to evaluate and define the core of biological engineering as VaNTH is trying to define curriculum in biomedical engineering [19]. There may emerge a set of fundamentals that undergird many of the interactions between biology and engineering. As this work progresses, one forum in which these different fields may come together is the American Institute for Medical and Biological Engineering [8], whose Council of Societies and Academic Council attempt to foster discussion on education.

Industrial Needs and Opportunities for Bioengineers

If we focus on BME, the question of "which industries?" to consult regarding educational needs becomes clearer. One can define at least three segments of industry that are relevant. The first includes the biomedical instrumentation companies: those engaged in production of imaging instrumentation, implantable electronic instrumentation, internal and external artificial organs, hospital and point-of-care diagnostic instrumentation, and therapeutic modalities. The second is the pharmaceutical and drug delivery-oriented companies. These first two categories are beginning to merge. For example, at least three companies, including Abbott Laboratories, the Cordis Division of Johnson & Johnson, and Boston Scientific are all seeking approval for coronary artery stents that release drugs to inhibit restenosis caused by smooth muscle cell proliferation. Another group of companies are engaged in tissue engineering [20] and other cell-

based therapies. At present this comprises a very small part of the job market for biomedical engineers, but it is likely to grow [20].

These companies all would seem to be ideal employers for biomedical engineers, the only engineers who have a deep appreciation of the complexities of physiological systems. There is no survey of companies to point to, but the author's observations, based conversations over the last five years with members of the advisory boards of the Biomedical Engineering Department and the McCormick School of Engineering and Applied Science at Northwestern, and interactions with industry panels sponsored by VaNTH and by the Chicago Universities Bioengineering Industry Conference (www.cubic-online.org), is that many managers and industrial laboratory directors do appreciate that there are good reasons to hire biomedical engineers for certain positions and for the unique skills that they bring to the table. Several different capabilities of biomedical engineers are mentioned in these forums, but among the most consistent are the ability to speak the languages of engineering and medicine, a familiarity with human physiology and pathophysiology, and educational breadth. (Breadth may contribute to the ability to lead teams of engineers; BMEs understand more of chemical engineering than electrical engineers do, and more of electrical engineering than chemical engineers do.) One can point to biomedical engineers with almost all job titles, and the situation is continuing to improve as more biomedical engineers are promoted within their companies. However, new BME BS graduates often have a difficult time finding jobs, especially ones that utilize their specific skills, and the understanding that biomedical engineers are the right engineers is not universal. Even if this is recognized at higher levels, it has often not propagated down to the human resources level where initial decisions about hiring are done. (In fact, placement offices on college campuses may not be suitably attuned to biomedical engineering, either.) In addition, the number of biomedical engineers hired by even large companies is modest, so locating jobs for graduates can be difficult. Few, if any, companies define themselves as biomedical engineering companies, and, although the prospects for biomedical engineers will continue to improve, there will still be a need for many mechanical, chemical and electrical engineers in the health care industry.

Among industry professionals who are opposed to or uncertain about hiring biomedical engineers, one consistently hears two themes or complaints. The first theme is that industry does not know what a biomedical engineer is, whereas they know what characterizes a chemical or mechanical engineer. The contradiction is that the curricula of those fields are not uniform

across universities, either, but industry's perception is probably correct that a *core* of knowledge and skills is shared by all chemical or electrical engineers. As a result of not being sure of a biomedical engineer's skills, industry is reluctant to hire one and risk learning later that the new hire didn't know how to apply some important principle. The second fear is that biomedical engineers are too broadly trained, and don't have depth in any engineering area. Some programs have tried to address this by instituting tracks at the undergraduate level, which may be helpful, but among more enlightened members of industry, it is sometimes precisely the breadth of biomedical engineers that is cited as their advantage. Therefore, it is now questionable that tracks provide a full answer. (As an aside, we know from experience that tracks also force faculty to teach a lot of different undergraduate courses.) These are the issues that we in academia need to address – perception that BMEs lack a common curriculum, and their breadth necessarily causes a limitation on the depth of their engineering abilities. To some extent this means that we need better communication between universities and industry about the capabilities of current graduates, but we also need to work on the curriculum.

A Content Core for Biomedical Engineering

Biomedical engineering programs exhibit a rich diversity, based largely on the research areas of their faculty. This diversity in programs is desirable, and is in the spirit of the ABET Engineering Criteria 2000, which encourages programs to define their own set of objectives for educating students, and then show that these objectives are being met, and that work is being done by a process of continuous feedback to improve curriculum [21]. Unfortunately, this flexibility does not help industry define the capabilities of a biomedical engineer. The approach of the VaNTH Curriculum Project is that programs do not have to agree on the entire curriculum, but should agree on some fraction of what biomedical engineers should know. We are seeking a core set of knowledge and skills that we call "key content." The key content could be covered in different ways at different universities.

One level of key content is in math and basic sciences: math through differential equations, a year of physics including mechanics, electricity and magnetism, and wave phenomena, and a year of chemistry are assumed. The amount of organic chemistry, the amount and types of biology, and the level of computer proficiency expected of BS graduates are unsettled issues. It is especially important to define the key engineering content that BME

programs have more control over. It seems fairly clear that all biomedical engineers need to know something about some topics: for instance, data acquisition, signal analysis, instrumentation, statistics, mechanics, and transport, but we will have to determine what the individual topics should be at some relatively fine grain size. Whether parts of other fields, such as materials science, imaging, etc. should be key topics remains to be determined. Some of the concepts proposed by those working on biological engineering or bioengineering may prove to be important for biomedical engineers. We will also need to solicit feedback on the extent to which key engineering topics should be integrated with biology and to what extent they can be taught separately. It would seem that combining engineering with biology should be more motivating and therefore provide learning gains for students who wish to solve biomedical problems. Integration may also provide some educational efficiency and allow the coverage of engineering principles in the context of appropriate applications.

In addition to defining topics, it is necessary to specify what a student can do with each one. Inert knowledge is not valuable; it will be the dynamic application of key concepts that will count for the student. This means that it is important to attach the appropriate verb to each concept to indicate a level of proficiency expected. "Know about AC coupling" will not be an element of key content, but "Explain the effect of AC coupling on signal acquisition" or "Design a high pass filter" might be. We expect to choose the verbs indicating proficiency from taxonomies of learning goals, such as Bloom's [22] or Biggs' [23] taxonomy.

The key content will provide a way for universities to gauge whether they are providing an education consistent with what (we hope) will become a national standard. This could be supported, for instance, by the Biomedical Engineering Society and/or the Council of Chairs of Bioengineering and Biomedical Engineering. We anticipate that formulation and adoption of the key content should make it clear that biomedical engineers know engineering fundamentals as well as anyone else, and that they typically can use the fundamentals in more areas. We believe that this will allow industry to see the value of hiring biomedical engineers.

At some universities it will probably not be necessary to change curriculum content markedly. Universities should cover the key content, but they would not have to cover these fundamentals in the same way. They need not fit into courses with specific names, but could be spread across the curriculum in whatever way made sense locally. Universities could, of course, choose to ignore some of the recommendations. Eventually we believe that it will be possible to

arrive at a “compliance score” that reflects the extent to which a university follows the recommendations for key content. Some of the key topics could be covered in elective classes, which students with a strong desire to work in industry would be advised to take. Students who have other career paths in mind could choose to ignore parts of the recommendations.

Once the key topics are identified, there will be considerable room left in the curriculum for each program to educate its students in specialized ways that take advantage of local expertise and provide depth in specific domains, such as biomechanics or optics.

Process issues

Others have considered what the biomedical engineering curriculum should entail, so we are not starting from scratch. Among the sources that we are consulting to create the key content are 1) The Whitaker Foundation Educational Summit documents [24], 2) papers about biomedical engineering curriculum, e.g. Desai and Magin [25], 3) texts about bioengineering, and 4) our domain personnel throughout VaNTH. However, no one has previously tried to assemble curriculum at the necessary depth and or to determine whether there can be consensus. Once an initial list is assembled, we will use a Delphi method [26] to refine it. Essentially this is an iterative community-based process for identifying important concepts or elements in any field, making sure that all voices are heard, bringing ideas forward, and seeking agreement. We will use a web-based survey instrument to allow voting on whether each element should be considered a part of the key content. The survey will also solicit ideas about what is missing. We will ask not only for a rating of the importance of having each topic in the list, but also what level of proficiency should be expected at the BS level – that is, what verbs should be used with each content element. The list will be refined based on feedback and sent for another round of voting and comment. Two or three iterations are expected to generate enough consensus that we can publicize the content, seek endorsement by professional organizations, and begin to use it as a yardstick for evaluating curriculum. A project called CDIO (conceive, design, implement, operate) based in the Aeronautics and Astronautics Department at MIT has provided a model of the process of specifying both content and proficiency [27].

We will solicit votes from at least 150 reviewers with roughly equal representation from several groups: first, faculty from around the country; second, recent alumni in industry; and third, industry managers in a position to supervise biomedical engineers. It is clear that

reviewers must work actively to avoid being parochial and look beyond their own backgrounds and/or product line. The idea is to find the key concepts for *all* BMEs.

Two Sides to Curriculum – Competency and Content

Up to this point we have focused on content or domain knowledge. It is also important to consider the "Core Competencies" as shown in Fig. 3. In any forum in which industry lists the characteristics of employees, non-technical skills are placed high on the list. At the very top appear to be communication skills, including writing, presentation and listening, and teamwork skills. VaNTH has defined additional competencies related to design, ethical awareness, people and project management, and lifelong learning, and is developing a taxonomy of these core competencies. These skills can be regarded as orthogonal to the domains of biomedical engineering. All biomedical engineers need all the core competencies, and they will apply them in only slightly different ways in their different areas of endeavor. The orthogonality is a VaNTH construct, but the recognition of the importance of core competencies is widespread. Most of ABET's "a-k Outcomes" expected of engineering graduates enumerate these skills, but only in general terms [28]. Three quarters of the topics in the CDIO "syllabus" for the education of Aero/Astro engineers is essentially a taxonomy of the core competencies [27]. While other efforts have been made to list the core competencies, VaNTH intends to go farther in operationalizing the elements, providing examples of how to integrate them with domain content, and devising methods to assess whether students actually have these skills.

Other Elements of Curricular Advice

The VaNTH ERC has created a website [2] that serves as its repository of curricular advice. The key content and core competency projects will use this as their vehicle for dissemination. In addition, the website has several other elements that are intended to help programs build or revise curricula in a way that is consistent with ABET guidelines and with the research in learning sciences that comprises much of the work of VaNTH [5]. VaNTH believes that the biomedical engineering curriculum should support the development of adaptive expertise, so that graduates can transfer their knowledge to new problems, learn from their mistakes, and pursue new opportunities and new jobs. The website currently contains:

- Information on the state of the art of curricula in bioengineering nationally

- Information on existing undergraduate bioengineering curricula at the VaNTH schools.
- Principles and recommendations for the creation of new or revised bioengineering curricula. This includes recommendations about both content and pedagogy.
- Links to web and text references and resources for curricular planners

The website is an evolving resource, and feedback on it is welcome.

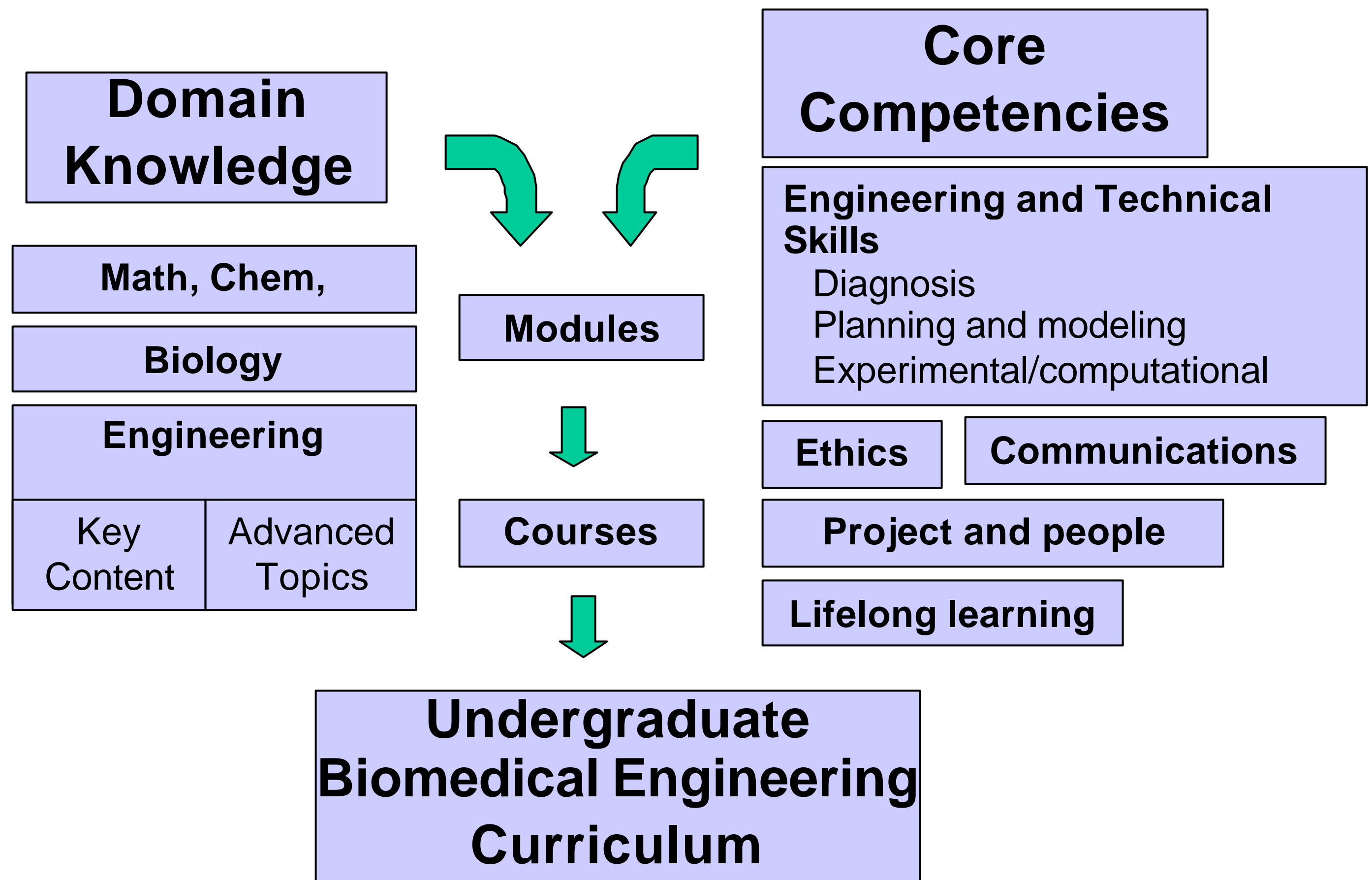

Figure 3. The two types of content that have to be blended to create a curriculum – domain knowledge and core competencies. The goal of the VaNTH curriculum project is to define and seek agreement on the portion of biomedical engineering content knowledge that all biomedical engineering graduates should obtain (key content). Advanced topics will be different by university and the student's area of specialization. The categories of core competencies are the working subject headings used at present by VaNTH. The center column illustrates the point that integration of the two streams may be the best method of learning.

Acknowledgements

I thank the many colleagues who continue to shape the points of view represented here, whether they realized it or not, including Drs. Thomas Harris, David Gatchell, Suzanne Olds, Kenneth McLeod, Douglas Lauffenburger, Jack Linehan, Richard Magin, Penny Hirsch, and members of the Council of Chairs of Bioengineering and Biomedical Engineering and the Academic Council of the American Institute of Medical and Biological Engineering. This work is supported by the National Science Foundation EEC-9876363.

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Biographical Sketch

Robert A. Linsenmeier received a BS in Chemical Engineering from Carnegie Mellon University and an MS and PhD in Biomedical Engineering from Northwestern University. After almost four years as an Assistant Research Physiologist at the University of California, San Francisco, he returned to Northwestern, where he has been on the faculty for twenty years. He is a professor of Biomedical Engineering, of which he served as chair from 1997 to 2002, and of Neurobiology & Physiology in the Weinberg College of Arts and Sciences, where he was director of the Integrated Science Program from 1993 to 1997. He has published more than 50 papers on mammalian retinal electrophysiology, microenvironment, and metabolism, with an emphasis on oxygen transport. Since 1999 he has been engaged in education research through the VaNTH ERC, of which he is Associate Director and leader of the Bioengineering Domain Thrust. In 2002 he was Chair of the Academic Council of the American Institute of Medical and Biological Engineering. He is a fellow of the American Institute of Medical and Biological Engineering and a senior member of the Biomedical Engineering Society.