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ROLES FOR LEARNING SCIENCES AND LEARNING TECHNOLOGIES IN BIOMEDICAL ENGINEERING EDUCATION: A Review of Recent Advances

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■ **Abstract** Education in biomedical engineering offers a number of challenges to all constituents of the educational process—faculty, students, and employers of graduates. Although biomedical engineering educational systems have been under development for 40 years, interest in and the pace of development of these programs has accelerated in recent years. New advances in the learning sciences have provided a framework for the reexamination of instructional paradigms in biomedical engineering. This work shows that learning environments should be learner centered, knowledge centered, assessment centered, and community centered. In addition, learning technologies offer the potential to achieve this environment with efficiency. Biomedical engineering educators are in a position to design and implement new learning systems that can take advantage of advances in learning science, learning technology, and reform in engineering education.

CONTENTS

INTRODUCTION

Biomedical engineering is growing rapidly as areas of research and knowledge, as educational programs, and as a body of practice in industry and health care. Keeping pace with this field requires a new kind of student—a student who can rapidly adapt to new information and recognize the potential for applying this knowledge to existing problems of human health and biology. Educating future generations of engineers who will be designing biomedical engineering innovations requires reflection on what we consider to be biomedical engineering and what we know about how people can learn it. This article provides a review of literature that focuses on approaches to biomedical engineering education and on pedagogical methods that can be developed to teach biomedical engineering. This literature review provides a summary of how biomedical engineering is defined, what knowledge the learning sciences provide to enhance biomedical engineering education, and how technology can be used to optimize the design of an effective learning environment for biomedical engineering. This work should serve as a lens to focus on biomedical engineering education and on methods that can be used to optimize learning opportunities for students at many levels.

STATE OF EDUCATIONAL PROGRAMS IN BIOMEDICAL ENGINEERING

What is Biomedical Engineering?

Definitions of biomedical engineering have been offered by professional organizations. The Biomedical Engineering Society (1) states the following as part of their career-guidance document:

> “A biomedical engineer uses traditional engineering expertise to analyze and solve problems in biology and medicine, providing an overall enhancement of health care. Students choose the biomedical engineering field to be of service to people, to partake of the excitement of working with living

> systems, and to apply advanced technology to the complex problems of medical care. The biomedical engineer works with other health care professionals including physicians, nurses, therapists and technicians. Biomedical engineers may be called upon in a wide range of capacities: to design instruments, devices, and software, to bring together knowledge from many technical sources to develop new procedures, or to conduct research needed to solve clinical problems."

The Whitaker Foundation presents the following definition aimed at defining research in biomedical engineering (2):

> "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.
2. The development of new devices, algorithms, processes and systems that advance biology and medicine and improve medical practice and health care delivery."

A number of academic programs in the field use the term bioengineering. Recently, Lauffenburger & Nerem (3) have emphasized the broader nature of bioengineering and discussed the impact of biological knowledge on areas of engineering beyond medical application. However, the substantial emphasis of most programs labeled bioengineering centers on eventual medical application. A significant number of programs exist that are labeled "biological engineering" or related names that have heavier emphases on food engineering, agricultural engineering, or environmental applications in bioremediation (4). The remainder of this discussion will focus on biomedical engineering (BME) education.

Growth in Educational Programs in Biomedical Engineering

Education in BME has evolved since about 1960 to a current state where there are 21 undergraduate programs accredited by the Accrediting Board for Engineering and Technology (ABET). Another 18 programs are accredited as biological systems engineering or biological engineering. Approximately 170 graduate programs in bioengineering, biomedical engineering, biological engineering, and biotechnology are listed in Peterson's Guide (5). These programs represent a broad range in focus and institutional culture.

The state of BME education has been reviewed by a number of authors over the years. An early attempt was a special issue of the *IEEE Transactions in Biomedical Engineering* in 1975 in which a number of topics were discussed. These included general discussions of the founding of BME, the then current situation and prospects for the field (6–8), engineering in health care (9, 10), educational approaches (11–17), and a discussion of the role of the biomedical engineer in the healthcare device industry (18). Many of these authors focused on the potential of biomedical engineering in hospital-based health care. Educational discussion centered on the appropriate training for that function and for medical research. The article by Schwartz & Long (12) provided useful data that captured the size of the biomedical engineering effort at that time. The paper did not deal explicitly with the subject matter of biomedical engineering. However, several trends were revealed. Subjects receiving discussion were instrumentation and monitoring devices, quantitative physiology, bioelectricity, ultrasound, medical computing, biofluid mechanics, and topics underlying clinical engineering.

The state of biomedical engineering education has been reviewed periodically since 1975 [e.g., Potvin et al. (19)]. In December 1999, the Whitaker Foundation sponsored an international summit meeting on biomedical engineering education. This meeting produced a significant body of data on programs in operation at that time (20). Table 1 presents a comparison of enrollments in biomedical engineering programs reported in 1975 (13) and at the summit in 1999 (20). This table shows substantial growth over the 24-year period in programs, enrollments, and graduates. The rates of growth have not been steady, however. Figure 1 shows the rate of growth of BME Ph.D. and B.S. (or similar baccalaureate programs) programs between 1960 and 2000 taken from the Whitaker Foundation Summit data (20). The rate of growth in Ph. D. programs has been relatively constant over the 40-year period. However, after an initial enthusiasm, the rate of growth in B.S. programs

TABLE 1 Comparison of biomedical engineering programs: 1973–1999

Program		**1973**[a]	**1999**[b]
Bach.	Number of programs	24	62
	Current enrollment	852	5546
	Ave. enrollment/progr.	36	89
	Grads	38[c]	952
M.S.	Number of programs	37	71
	Current enrollment	505	1106
	Ave. enrollment/progr.	14	16
	Grads	87[c]	452
Ph.D.	Number of programs	38	74
	Current enrollment	412	1967
	Ave. enrollment/progr.	11	27
	Grads	49[c]	245

[a]1973 data reported in Reference (12).

[b]1999 data from Whitaker Summit summary [Reference (20)].

[c]Average of graduates from 1965 to 1973.

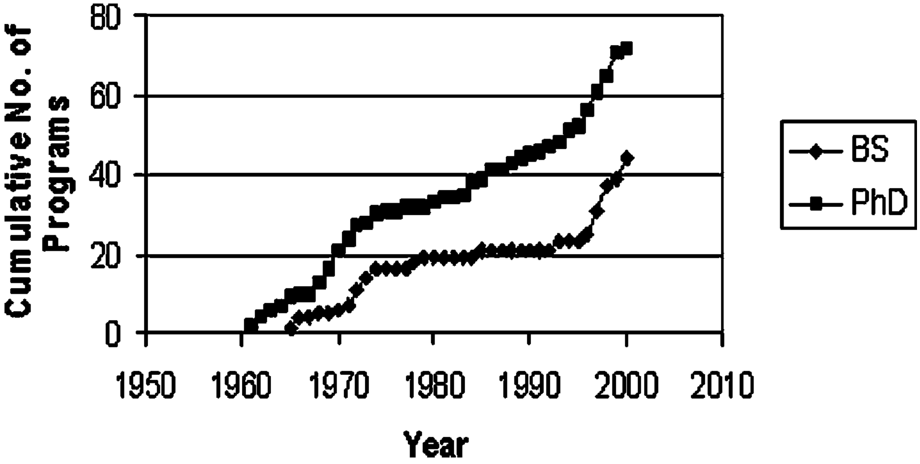

Figure 1 Cumulative number of programs in biomedical engineering as a function of time.

remained low (less than one/year average) from 1975 until about 1995. Since 1995, the number of B.S. programs has almost doubled. The growth in Ph.D. programs probably shows the general maturation of research and development in the domain subjects generally included in biomedical engineering. The general explosion in biological knowledge and possibilities has undoubtedly stimulated such development. In addition, a substantial biomedical device industry has arisen which has provided opportunities for BME graduates. This general growth has in turn affected institutional decisions regarding B.S. education. Such programs generally require a greater institutional commitment than a graduate program and, apparently, have been more difficult to found. The Whitaker Foundation has maintained a grant program aimed at stimulating the development of B.S. programs and departments in biomedical engineering. This substantial funding source has undoubtedly stimulated the rate of B.S. program growth for the past five years. However, the figure shows that the formation of B.S. programs had probably been deferred excessively during 1975 to 1995, and some of the more current growth may be correcting for that neglect. It should also be remembered that a number of major paradigm shifts in biology, engineering, and medicine occurred during the 20 years between 1975 and 1995. These included the computing/communications revolution, the development of genetic and molecular biology at unprecedented rates, significant alterations in health care funding (which may have slowed the development of clinical engineering), and shifts in defense research and development due to the end of the Cold War. These substantial alterations necessarily occupied administrative and financial resources that might have otherwise overseen the growth of BME at a steady rate. Most of these events are currently acting to stimulate growth and interest in the knowledge underlying BME and are partial causes for the current high rate of growth.

Reform in Engineering Education

The National Science Foundation has supported a number of coalitions (21) aimed at curricular reform and development of learning technology to improve undergraduate engineering education. Five of these coalitions (Succeed, Gateway, Ecsel, Foundation Coalition, Synthesis) are geographically diverse and are aimed at general issues mainly, though not exclusively, associated with the first two years of the engineering curriculum. Another three organizations (Engineering Academy of Southern New England, SCCEME, and Greenfield) were aimed at particular geographic regions (New England, Southern California, Michigan) and were originally designed to address employment and training for manufacturing engineering. All of these organizations have undertaken extensive studies on methods to reform early, and in some cases more advanced, engineering education. All have had as a goal increased recruitment and retention of students to engineering, especially women and underrepresented minority students. They have emphasized design and, in some cases, research as tools to spark interest in engineering and science fundamentals, breadth in ethics, professionalism and business, interaction with the actual working environment of engineering, outreach to precollege and working populations, and the broad utilization of learning technologies. In two cases (Gateway and Succeed), a special emphasis on the importance of biology and biotechnology was included.

In 1998, the National Science Foundation announced a competition for an Engineering Research Center in Bioengineering Educational Technologies. This center was awarded to a partnership led by Vanderbilt University that included Northwestern University, the University of Texas at Austin, and the Harvard/MIT Health Sciences and Technology Program (VaNTH ERC). This group identified a number of issues regarding education in biomedical engineering that they judged were in need of new effort or review. These were as follows (22):

(*a*) How can undergraduates be properly trained in both biology and engineering within the constraint of a four-year bachelor's degree program?

(*b*) How can students be prepared for and be introduced to the actual practice of BME in businesses, industries, and health care organizations?

(*c*) What academic organizations will foster BME education at all levels?

(*d*) How should BME relate to other academic programs in engineering, health professions, and life science?

(*e*) What are the roles of businesses, industries, and hospitals in BME education?

(*f*) How can the special complexities of BME be addressed—bioethical questions, complicated regulatory environment, rapid rates of obsolescence for graduates and teachers?

(*g*) How can instructors cope with the very limited amount of teaching material for BME?

(*h*) What are emerging biotechnologies and how should they be taught?

(*i*) How can realistic laboratory exercises be created?

(*j*) How does one teach the greater uncertainties in design that are inherent in technology aimed at living systems?

(*k*) At the doctoral level, what should be the balance between training in biological and engineering science methodologies?

These investigators proposed a project aimed at synthesizing new work in learning science and learning technology with the domain areas of biomedical engineering in order to address these issues.

ADVANCES IN LEARNING SCIENCES RELEVANT TO BIOMEDICAL ENGINEERING

Research on learning and cognition can provide a strong foundation for significantly improving BME education. For example, a great deal is now known about the cognitive processes and knowledge structures that characterize expertise in such diverse areas as physics, electronics, mathematics, medical diagnosis, chess, history, and other subject matters (23–27). Research shows that experts' strategies for thinking and solving problems are closely linked to rich, well-organized bodies of knowledge about subject matter (24, 25, 28, 29). Experts' knowledge is connected and organized around important concepts (e.g., Newton's second law of motion); it is "conditionalized" to specify the contexts in which it is applicable, and it supports understanding and transfer rather than only the ability to remember facts and formulas. Novices' initial interpretations of problem situations tend to focus on surface features of problems rather than on important conceptual ideas (25); novices often "search for formulas" rather than begin by thinking qualitatively about problems. These initial intepretations (representations) have an important impact on the subsequent direction of the problem-solving process (30). The ability to fluently recognize and interpret meaningful patterns of information is an extremely important characteristic of expertise (29, 31).

Research also reveals that people can reach a level of skilled expertise in a discipline without becoming adaptive experts. Adaptive experts have acquired a combination of flexible knowledge, skills, beliefs about themselves as learners, and attitudes toward new learning that set the stage for lifelong learning (32–35). An emphasis on adaptive expertise brings with it new methods for assessing the quality of learning and transfer (36). Accompanying the research on expertise is research that explores the kinds of learning experiences that lead to the development of adaptive expertise and flexible transfer to new settings (36–38). Many traditional teaching methods are less than effective for developing adaptive expertise. For example, a major problem with teaching that overemphasizes lecture- and text-based presentations of facts is the "inert knowledge" problem (39). People can retrieve specific facts and procedures when specifically prompted to do so (e.g., in the context of many multiple choice tests) yet have failed to learn when, how, and why to use this specific knowledge to solve new problems. In cognitive science terms, their knowledge is in the form of propositions and procedures that are not conditionalized (40–42). As noted earlier, conditionalized knowledge is an important characteristic of expertise.

A great deal has been learned about ways to develop useable (conditionalized) knowledge. Assigning practice problems and asking students to work in laboratory settings represent familiar strategies for helping students develop conditionalized knowledge that supports problem solving (29). Nevertheless, there is much room for improvement. For example, (*a*) practice problems are often too simple and too explicitly cued to help students develop the patterns-recognition skills needed for authentic problem solving (31); (*b*) even given problems of appropriate complexity, students' knowledge is often tied to the surface features of the problems they attempt to solve and hence may be overly contextualized (43–46); (*c*) students often benefit much more by working with a set of carefully crafted problems prior to hearing a lecture or reading a text rather than vice versa (38); (*d*) students often are not introduced to models of experts' initial qualitative thinking as they solve particular problems, hence the students practice using less-than-ideal strategies (47); and (*e*) students can learn to solve sets of practice problems yet never have the opportunity to identify and correct preconceptions that they bring to the learning setting (47, 48). Without opportunities to identify preconceptions and think them through, students' later abilities to solve problems can be impaired (47, 48).

One approach to instruction that may be useful in BME education is enhanced use of case-based, problem-based, and project-based learning, where students' learning is organized around attempts to solve authentic problems that occur in the domains of biomedical engineering. Methods such as these have been used in medical schools, law schools, business schools, and increasingly in other areas such as engineering, mathematics, and science [e.g., see CTGV (49) for examples in science and mathematics; Kolodner (45) and Schwartz et al. (50) for examples in engineering]. Data indicate that, when used appropriately, these methods can help students develop the conditionalized knowledge and understanding that lets them think productively about problems in the discipline (49, 51–54). However, the methods must include opportunities to work in multiple contexts (55), identify preconceptions that are relevant to the problem solving [e.g., Minstrell (48)], formatively assess progress as one proceeds throughout problem solving, and engage in reflection and revision following the assessment in order to prepare for some kind of summative (as opposed to formative) assessment (38, 50, 49, 56, 57). Opportunities to work collaboratively, if used appropriately, can enhance students' abilities to learn (58).

New developments in the science of learning also emphasize the importance of helping people take control of their own learning. Because understanding is clearly important, people must learn to recognize when they understand and when they need more information. What strategies might they use to assess whether they understand someone else's intent? What kinds of evidence do they need in order to believe particular claims? How can they build their own theories of phenomena and test them effectively?

Many important activities that support active learning have been studied under the heading of "metacognition," which refers to people's abilities to predict their performances on various tasks (e.g., how well they will be able to remember various stimuli) and to monitor their current levels of mastery and understanding (59, 60). Teaching practices congruent with a metacognitive approach to learning include those that focus on sense making, self-assessment, and reflection on what works and what needs improving. These practices have been shown to increase the degree to which students transfer to new settings and events (61, 62). Collaboration among peers, both face-to-face and electronically, can help students receive feedback about their thinking and learn with understanding.

Much of this previous work has been recently summarized in a report from the National Academy of Sciences entitled "How People Learn: Brain, Mind, Experience, and School" (63). Overall, research on expertise and learning suggests designs for learning environments that include at least the following features: (*a*) They are learner centered in the sense that they take into account the knowledge, skills, preconceptions, and learning styles of the learners; (*b*) they are knowledge centered in the sense that they help students learn with understanding by thinking qualitatively, organizing their knowledge around "key concepts" or "big ideas" of the discipline and understanding the conditions under which different aspects of their knowledge are applicable; (*c*) they are assessment centered in the sense that they provide frequent opportunities for students to make their current thinking visible so their understanding can be refined as needed (ideally this is done prior to summative assessments such as tests); and (*d*) they are community centered in the sense that they foster norms that encourage students to learn from one another, plus encourage faculty to do likewise. A diagram of these concepts is shown in Figure 2.

TECHNOLOGY SUPPORT FOR LEARNING

Roles for Technology

A recent review of the literature on the effectiveness of learning technologies (over 700 papers) showed that its effectiveness generally decreased as the level of education of the students increased. Thus, this analysis argued that learning technologies were less effective in higher education (64). Despite this argument, there is evidence that learning technology linked with new ideas from learning science can result in increased effectiveness in students' learning.

New technologies—including computers, CD ROMS, DVD, networking, and Internet technologies—make it possible to utilize insights from learning theory to significantly enhance the quality of both student and faculty learning. Examples are briefly summarized below.

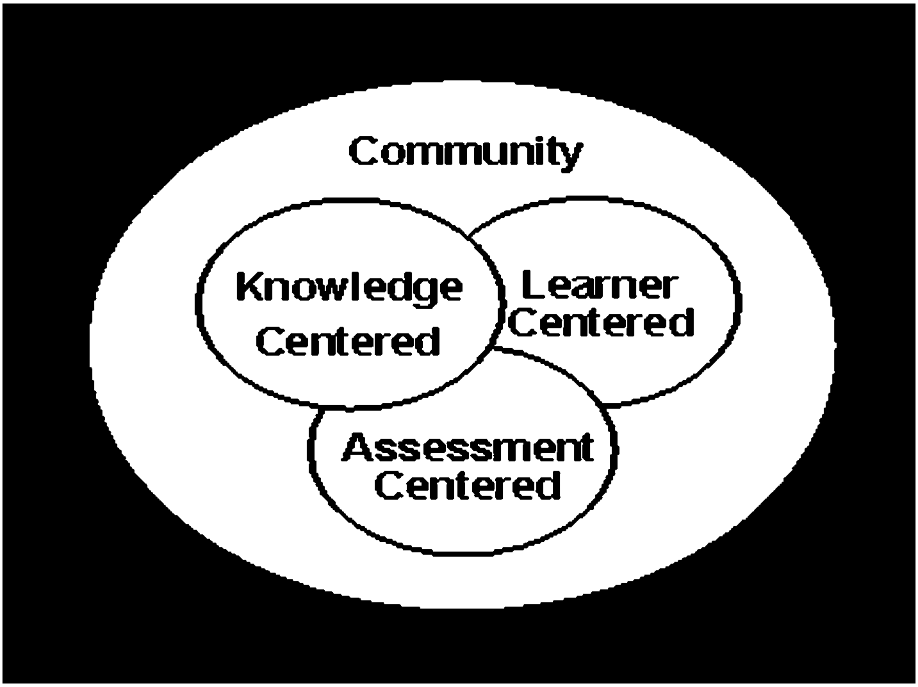

Figure 2 The How People Learn (HPL) environment.

BRINGING AUTHENTIC PROBLEMS INTO CLASSROOMS New technologies enhance problem finding and problem solving by introducing authentic real-world problems on media. New media player technologies make it much easier to search and explore complex cases relevant to areas such as medicine, biology, mathematics, and, perhaps, BME. Teachers can instantly access important events to use as illustrations; students can easily return to specific scenes in order to explore them more fully. This flexibility is very important for helping students achieve in-depth understanding of events [e.g., see CTGV (49)]. Simulation environments can also introduce realistic problem situations. Simulations support a particularly active form of learning because students can manipulate the simulations and see the consequences.

RESOURCES AND TOOLS TO SUPPORT PROBLEM SOLVING In addition to introducing students to complex problems, technology serves as a scaffold for solving these problems by enabling them to seek assistance from outside the classroom and by enhancing their work through the use of powerful tools. The World Wide Web (WWW) brings an enormous database of information into the classroom. These resources make use of hypermedia through which dynamic images, sound, and text can be seamlessly woven together and flexibly organized. When compared with text-based resources, electronic references are easier to search and to update (65). Online conferences provide both synchronous and asynchronous opportunities for students to solve engineering problems or to write about their work and discuss it with classmates and experts both locally and at remote locations. [e.g., see Bourne (66), Koschman (67), Bereiter & Scardamalia (68)]. Tools for problem solving include word processing, spreadsheets, visualization programs (e.g., CAD), and interactive simulations and programs for mathematical modeling (e.g., MatLab). Students can also be helped to invent their own electronic-based tools and hence learn to "work smart" [(e.g., see Bransford et al. (69)].

OPPORTUNITIES FOR FEEDBACK, REFLECTION, AND REVISION New technologies make it easier to provide the feedback that students need in order to revise and refine their thinking. Computer-based simulations and tutoring environments serve this function (70, 71). Spilker et al. (72) have developed instructional modules in mathematics to be used across the curriculum (the Links Project). Electronic Web-based "challenges" have been used to encourage students to test their current understanding of a topic by attempting to solve a series of problems, posting their answers to a website, and then receiving automatic feedback. These challenges are motivating and increase student learning as well (49). Teachers' opportunities to provide feedback can be increased with technology. For example, a computer-based tool for providing feedback on student-generated blueprints cut in half the time teachers needed to help students improve their work (49). Problem-simulation environments can provide students with a template of their decision-making process that can be compared with experts and other students (73). Tools like this can help teachers determine if students are being strategic in their process or simply using trial and error. Classroom-communication technology is another valuable tool that allows teachers to pose questions during class and get immediate responses from the students (74). This kind of technology provides both the teacher and students with an indication of what they are learning or not learning. These kinds of feedback technologies target both a learner-centered and assessment-centered focus to help instructors keep a closer focus on how well their instruction is helping students develop requisite skills and knowledge.

COMMUNICATION AND COMMUNITY BUILDING Communication technologies are vital in linking students inside and outside the classroom. Online conferences among classmates allow students to discuss academic issues. Conferences can also be asynchronous, so students don't have to interact at the same time. Electronic conversations can create a permanent database that supplements the fleeting oral conversation of an in-class discussion.

Web-Based Learning

The last year has seen a growth of interest in e-learning as a business opportunity. Merril Lynch published a research document (75) outlining the potential for a $250B market in e-learning at all levels. This current wave of activity in e-learning has created an impetus for standards that provide content developers and delivery-system developers a shared view of how learning content will be structured, packaged, and delivered. These standards aim at providing some assurance that the platforms under development can deliver the learning content under development. The new standards, such as the Advanced Distributed Learning (ADL) Initiative's Shareable Courseware Object Reference Model [SCORM (76)], are being developed. As a way of making content more reusable, the standards see content integration (i.e., navigation) described outside of the content itself. Presently, there are no commercially available authoring systems that generate courseware compliant with ADL's SCORM standard. There is a body of work that addresses features of such a system, such as delivery sequencing and the reuse of learning objects (77). Other features are left unsupported, such as the explicit definition of learning objectives, the association of learning objectives with content elements and domain concepts, and the collection of metadata required by standards such as SCORM.

Research on courseware-authoring systems has been conducted for over two decades, with a particularly high level of activity in the mid-1990s in the area of intelligent tutoring systems [ITS (78)]. ITS bring together explicit models of expertise (domain knowledge), instructional strategies, and student knowledge with the aim of using the instructional strategies to align the student's knowledge with the expert's knowledge. Significant work remains in constructing courseware-authoring tools that incorporate learning science and are tailored to the domain of biomedical engineering.

Research on the value of asynchronous learning as a pedagogical method has been vigorous for the past several years. A website exists for an online journal dedicated to this topic (79).

CURRICULUM ISSUES IN BIOMEDICAL ENGINEERING EDUCATION

Few discussions of biomedical engineering in the literature have emphasized the actual subject matter of biomedical engineering that should be included in a curriculum. The curriculum should consist of three elements: a selection of crucial knowledge upon which the field rests and which is necessary for effective practice ("knowledge centered"), a set of skills and techniques that allow the use of the knowledge, and effective pedagogical strategies for the transmission of knowledge and development of skills.

A BME curriculum is a restricted choice of taxonomical segments of biomedical engineering knowledge combined with pedagogical strategies to convey the most vital information in a fixed period of time. Two major questions are then produced: What parts of the taxonomies are most vital at a particular time, and which strategies should be employed to teach them? The preceding literature discussion provides a basis for answering the latter question. The first question is more difficult, and the answers depend on many factors. There are at least three ways that the crucial taxonomic elements could be identified. They are as follows: (*a*) a survey of existing curricula would be useful because it represents actual choices and experiments in curriculum design that, for accredited programs, have passed internal and external peer review (ABET criteria provide general guidelines); (*b*) an analysis of biomedical engineering knowledge (taxonomies) that gives potential curricula based on the intellectual content of the field; (*c*) a survey of students and industries to identify gaps and problems in core education that practitioners and the employers of practitioners have identified. Each of these methods has drawbacks. Existing curricula may be rooted in previous analyses and traditions. Knowledge taxonomies per se will not show what section of the knowledge structure has the highest priority for a particular curriculum. Discussions may be based on research or scientific interest rather than actual needs of future practitioners. Students and industries may take excessively parochial and narrow views of what is important. They also may not see the link between fundamental knowledge and effectiveness as a practitioner. Further work is clearly needed to illuminate a method by which effective biomedical engineering curricula may evolve.

Although there is still considerable debate about the exact content appropriate for BME curricula, the Whitaker Foundation summit (20) suggested the following areas as key for BME.

Basic:

- Biomechanics
- Bioinstrumentation
- Biosystems
- Cell/molecular Engineering
- Biomaterials

Advanced:

- Functional genomics
- Biomems (bio-micro-electro-mechanical systems)
- Cell/tissue engineering
- Computational Biology
- Bioimaging

A number of specific curricula were outlined on the Whitaker Summit database (20). Two recent papers have reviewed curricula at their own institutions. Ghista (80) has reviewed plans for new biomedical engineering curricula that responds to perceived needs for engineers to support tertiary care in hospital settings in India. The discussion outlines topics to bring BME students into closer contact with clinical science and health care. Desai & Magin (81) discussed a new curriculum at the University of Illinois at Chicago that emphasized cell and tissue engineering. This choice was influenced by experience of undergraduates seeking graduate opportunities in those fields and by discussions with industrial advisors.

American undergraduate BME curricula will use the guidelines of ABET to determine the skill sets that each curriculum needs to develop. Outcomes measures needed to assess the success of a given curriculum should provide guidance to curriculum planners. The ABET system has been discussed by Besterfield-Sacre et al. (82).

BARRIERS TO BE OVERCOME

Harris (22) has discussed barriers that exist to the development of biomedical engineering education. The nature of these barriers is discussed below.

Barrier 1: The Biology-Engineering Barrier

In 1974, the National Academy of Engineering published (83) a report that contained the following statement:

> "Yet even in the United States it is frequently observed that there is a considerable gap between the state of the art of the various engineering disciplines and the engineering that is actually applied to the problems of medicine and biology. The existence of this technology gap in a world that put men on the moon and transmits live color television instantaneously from continent to continent and, moreover, in an area (namely, health) in which each member of the human race has a very important stake would be astounding if it were not so widespread and of such long standing."

Significant effort has been expended to close this gap since 1974. However, barriers remain in the articulation between biology and engineering. A good example is educational background. Engineering students pursue a course of study heavily influenced by mathematics and physics. Biology students may take some introductory calculus, but it is rarely integrated into biological courses at any level. Engineering curricula incorporate physics, mathematics, and chemistry as important fundamental sciences, but biology is included in only specialized situations (such as biomedical engineering curricula). Further, even biomedical engineering undergraduate programs struggle with the need to provide students usable knowledge in both biology and engineering in four years. Although there are elements of tradition, organizational and curricular conservatism, and other sociological aspects to this barrier, the main elements are simply the complexity of the living state, the difficulties inherent in applying quantitative methods to living systems, and the time available for students to achieve meaningful understanding of the constituent sciences and bodies of practice in biomedical engineering. Pioneering programs in biomedical engineering have made major steps in educating students to synthesize biology and engineering. However, both biology and engineering are developing separately at rapid rates. Thus, efficiency is needed to provide students with understanding of both fields and with the communications tools necessary for collaboration among domain experts interested in common applications or the solution to broad problems. Other elements of the barrier include research methods and approaches and the organization of practice and industry. Other than a few strong clinical engineering programs, health care has yet to organize an effective way to engage engineers in medical technology application and management. Biomedical device and biotechnology industries also face significant knowledge gaps as their staffs move into new areas. A better education at all levels would help overcome this barrier.

Barrier 2: The Learning Science-Engineering Education Barrier

The preparation of engineering faculty for their teaching functions has historically been on-the-job training. Typical engineering faculty members bring an excellent fund of domain knowledge, but only their experience with previous teachers as the main preparations for a career in higher education. Because it is ordinarily at least half of their everyday responsibility to deal with students, courses, and curricula, a significant barrier to attaining knowledge in domain-relevant educational concepts for higher education exists. Recent efforts by NSF, the American Society for Engineering Education, and ABET have helped to address this barrier, but little of this effort has been addressed directly to biomedical engineering. Further, significant difficulties remain in conveying sound educational theory and practice to engineering educators either as graduate students (the ideal time for such education) or as beginning faculty members.

Barrier 3: Technology-Education Barrier

In spite of many efforts at bringing technology to bear on higher education, faculty skepticism remains high (a recent survey shows only 25% of professors use technology in their classrooms or laboratories). Skepticism is sometimes highest in engineering faculties. There are numerous causes, but the availability of good materials and lack of proven efficacy are two of the more prominent. A further barrier exists in the slowness with which traditional publishers are stimulating the development and beginning the dissemination of truly modular, digitally-based materials.

Barrier 4: The Academe-Industry/Practice Barrier

This problem is particularly acute in biomedical engineering due to the relative immaturity of certain aspects of the field, and the general separation of industry and academic work that exists. Only a few large biomedical device companies exist. Much industrial activity is based in smaller companies with few resources to dedicate to academic cooperation. Bringing academic research investigators to appreciate the problems of industry and bringing industry to see the potential of biomedical engineering ideas and people needs additional effort.

SUMMARIZING STATEMENT

Biomedical engineering education has a 40-year history in the United States. Growth has not been steady, but over 70 programs are currently in operation, many of them starting in the past ten years. Whereas this experience has led to the definition of certain areas that constitute essential knowledge in biomedical engineering, a significant number of challenges and barriers to complete development of education in biomedical engineering exist. Learning science and learning technology have the potential to meet these challenges and lower the barriers, but much work remains to bring this knowledge to bear on the field of biomedical engineering.

Advances in learning science can have import for the practical design of teaching materials using new technologies. A great deal of work has occurred in engineering to apply these technologies to education in restricted settings as discussed above. However, the next level of engineering learning technology needs to be synthesized with insights from learning science such as the HPL framework. These ideas will lead to design principles for next-generation learning technologies.

We also conclude that very little of this effort in learning technology has been institutionalized into engineering schools and even less into biomedical engineering educational programs. Licensing systems for engineers have a limited effectiveness in assessing and guiding biomedical engineering development. The new ABET accreditation system has considerable promise to help in systematization, but it is a general set of criteria that needs further refinement for application to biomedical engineering.

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The *Annual Review of Biomedical Engineering* is online at http://bioeng.annualreviews.org

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