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Bioengineering/Biomedical Engineering Education and Career Development: Literature Review, Definitions, and Constructive Recommendations*

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Bioengineering/Biomedical engineering education has evolved since the late 1950s and is progressing in leading academic institutions around the world. Today, bioengineering/biomedical engineering is considered to be one of the most reputable fields within the global arena, and will probably be the primer for any future breakthroughs in medicine and biology. This paper is intended to provide a detailed study of career development in Bioengineering/Biomedical Engineering, together with a set of strategies and recommendations to be pursued by individuals and/or entities seeking to plan and design careers and/or curricula in this field. The paper aims to address the international student who is considering bioengineering/biomedical engineering as a career, with an underlying emphasis on students from developing and transitional countries where career guidance is lacking. The paper is also addressed to academic institutions of higher education, ministries of higher education, and other governmental agencies, mainly within such countries, who intend to launch or reform their bioengineering/biomedical engineering curricula. A comprehensive undergraduate curriculum that has been recently implemented at the American University of Science and Technology, Beirut, Lebanon, is presented here as a prototype of a modern well-developed curriculum in Biomedical Engineering. This program is considered to be one of the regional premier curricula in Bioengineering/Biomedical Engineering. The paper also provides a thorough review of the literature followed by a comprehensive definition of the field and its subdivisions.

Keywords: biomedical engineering; bioengineering, education; career development; curriculum

INTRODUCTION

BIOENGINEERING/BIOMEDICAL ENGINEERING EDUCATION has evolved since the late 1950s and is now advancing in leading academic institutions worldwide [1–3]. Officially, the first Biomedical Engineering program was launched in 1959 at the Master's level at Drexel University (Philadelphia, PA, USA) to be soon followed by Ph.D. programs at Johns Hopkins University (Baltimore, MD, USA) and the University of Pennsylvania (Philadelphia, PA, USA) [4]. Today, we are witnessing a rapid rise in the development of new curricula in Bioengineering/ Biomedical Engineering around the world. These programs are quite diverse and vary in academic content, as well as within the different topics constituting the various areas of Bioengineering/ Biomedical Engineering. While there has been no consensus about a single curriculum in Bioengineering/Biomedical Engineering, and perhaps there won't be any in the near future, there has long been a trend by authorities in the field towards orienting the curricula in an optimal direction. Nevertheless, and to the best of the author's knowledge, a literature search revealed that no explicit and comprehensive study pertaining to career guidance in Bioengineering/Biomedical Engineering has been reported. Career guidance in this field has mostly been gleaned from professional societies and organizations. This paper is intended to provide a comprehensive study of career development in Bioengineering/ Biomedical Engineering, together with a set of strategies and recommendations for individuals seeking to plan and design careers in this field. This paper aims to address the international student who is considering bioengineering/biomedical engineering as a career, with an underlying emphasis on students in developing and transitional countries where career guidance is lacking. The paper is also addressed to academic institutions of higher education, ministries of higher education, and other governmental agencies, mainly within such countries, who intend to launch or reform Bioengineering/Biomedical engineering curricula. As a prototype of a modern well-developed curriculum in Bioengineering/ Biomedical Engineering, a comprehensive undergraduate curriculum that was recently implemented at the American University of Science and Technology, Beirut, Lebanon, is presented here.

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This program is considered to be one of the best curricula in Bioengineering/Biomedical Engineering in the region [5].

Before discussing this, the reader is cautioned about the use of the terms bioengineering and biomedical engineering. There exist some discrepancies concerning these two terms. Some authorities use the term bioengineering as a 'broad umbrella' that encompasses biological engineering, biomedical engineering, medical engineering (commonly referred to as clinical engineering), as well as biochemical engineering [6, 7]. Others define bioengineering as 'a basic-research-oriented activity that is closely related to biotechnology and genetic engineering', whilst biomedical engineering is considered, by these authorities, to be the 'broad umbrella' term that encompasses the above areas, among others [8]. Notwithstanding this paradox, it should be recognized that there is a great degree of overlap between these two fields. Accordingly, one can solve this problem by looking at the existing ambiguity from two different perspectives: *morphological* and *occupational*. Morphologically speaking, the difference between the terms bioengineering and biomedical engineering is the absence of the word '*medical*', defined in the dictionary as '*the practice of medicine*' and which in turn is implemented in both Bioengineering and Biomedical Engineering. Hence, there is no dichotomy between these two terms: in fact they are complementary. From an occupational perspective, Harmon in 1975 stated that 'Bioengineering is usually viewed broadly as a basic-understanding field that uses the tools and concepts of the physical sciences to analyze biological systems; thus it is largely research oriented and not necessarily related to medical problems' [9]. He added that 'While the prime focus of biomedical engineering is on utility, it combines clinical emphasis with strong commitment to basic research'. In another paper, Katona asserted that 'there is no consistent distinction between academic departments bearing one or the other designation and the two terms are often used interchangeably' [10].

There is no doubt that the current century reflects an age of medical renaissance that encompasses and fosters both fields. Accordingly, this paper refers to bioengineering and biomedical engineering *interchangeably* and in depth.

Bioengineering/Biomedical Engineering is currently considered amongst the most reputable fields within the global arena, and will probably be the primer for any future breakthroughs in Medicine and Biology. Current advancements in healthcare practices are being guided toward new challenging frontiers, such as functional genomics, stem-cell therapy, organ growth, tele-surgery, spinal cord repair, and artificial vision.

Today, the field of Bioengineering/Biomedical Engineering, with its steadfast growth, has triumphantly leaped into such interesting domains as: bioinformatics and computational biology; biomedical imaging and image processing; biomedical sensors and biomedical instrumentation; biomimetics and biomicroelectromechanical systems (BioMEMS); biosolid- and biofluid-mechanics; biorobotics and biomechatronics; biosystems processing and biosystems modeling; biothermodynamics; cardiovascular and pulmonary systems; clinical engineering; drug delivery and gene therapy; healthcare information technology; micro- and nano-biomedical sciences and technologies; molecular, cellular, and tissue engineering; neural and rehabilitation engineering; and genomics and proteomics.

LITERATURE REVIEW

In 1975, the *IEEE Transactions on Biomedical Engineering* published what could be perceived to be amongst the earliest comprehensive special issue on Biomedical Engineering Education and Employment. This special issue consisted of 13 papers that, according to Harmon, discussed many of the challenges pertaining to Biomedical Engineering as 'a relatively new interdisciplinary profession striving for identity, quality control, and acceptance' [9]. Seven of these papers have been found pertinent to this study and are presented here. In his paper, Harmon raised a set of meta-questions pertaining to biomedical engineering education, specifically 'how to do what, with which, and to whom' [9]. He stated that since the ultimate role of the biomedical engineer is to serve society, emphasis in biomedical engineering education should be centered on application rather than on research. Subsequently, flexible modular provisions within the multi-tracked biomedical engineering programs are needed to produce equally heterogeneous biomedical engineering practitioners. Jacobs discussed the sociological and technological factors that were significant in the inception of the science of biomedical engineering [11]. He argued that Biomedical Engineering had become a recognized health-related profession because of its marked difference from the traditional engineering disciplines. He concluded that the demand for well-trained individuals in biomedical engineering sciences was perceived to be 'insatiable' at that time. Johns' thesis in his paper, '*Current Issues in Biomedical Engineering Education*', pivoted around the fact that Biomedical Engineering has to recognize and foresee the political, social, and economical changes within its external environment so as to define and set the goals and objectives of its educational programs [12]. In his paper, Weed debated whether biomedical engineering should be 'practice *or* research?' or 'practice *and* research?' [13]. He stated that, at the time, Biomedical Engineering had been recognized in universities and medical research hospitals, as a field that tended to produce biophysics–physiology research-oriented biomedical engineers; thus, causing a major deficit in the employment of such a biomedical engineer

Table 1. Summary of reported results from Schwartz and Long (1975) [15]

Total U.S engineering schools surveyed (early months of 1974)	**222**
Schools having degrees or programs in BME	121
Schools with no programs or degrees in BME	76
Schools who did not respond	25
Schools awarding degrees in BME	**49**
BS degree	25
MS degree	37
Ph.D. degree	38
Schools offering options or programs in BME in which the student received some other engineering degree	88
BME student enrollment for the 1973 fall semester	**3769**
BS degree	1530
MS degree	1306
Ph.D. degree	933
BME degrees awarded between 1965 and 1973 fall semester	**2889**
BS degree	574
MS degree	1424
Ph.D. degree	891

in the biomedical industry who preferred to be a classical electrical, mechanical, or computer engineer. He concluded that educational programs should aim for the following expertise: 'the basic biomedical engineering research scientist, the technology interface engineering expert in health care delivery, and the biomedical design engineer for industry.' Mylrea and Sivertson addressed the potential of Biomedical Engineering versus its reality in healthcare [14]. They stated that, while Biomedical Engineering gained vast recognition, its application in healthcare did not meet the hoped-for expectations. They proposed that in order to expedite the synergistic interaction between engineering and healthcare, the following needs have to be met: (1) 'Expanded and successful use of clinical engineers in health care institutions'; (2) 'the development of relevant educational curricula and a continuum of medical engineering education'; and (3) 'early involvement of biomedical engineering in the planning of health care delivery at Federal, State and district levels.'

Schwartz and Long quantified the results obtained from a survey analysis of biomedical engineering education performed in 1974 jointly by the American Society for Engineering Education and the Engineering in Medicine and Biology group of the IEEE [15]. The objective of this survey was to 'identify all the engineering schools in the U.S. that had Biomedical Engineering degrees, options or programs' so as to study the academic growth of biomedical engineering as a new career. This survey used a questionnaire that was sent to 222 engineering schools, and a summary of its major findings is presented in Table 1. Kahn, from his personal experience with bioengineers in the medical instrumentation industry, reflected on the subject of biomedical engineering education for employment by industry [16]. He stated that despite the significant key roles that had emerged in the industry for trained bioengineers, there were a number of shortcomings that precluded them from finding challenging and leading jobs. He argued that, this was partially due to the discrepancy between the level of development of the biomedical industry and the type of training received by the bioengineers. He then emphasized that since neither hardware orientation nor management was a major part of their training or experience, bioengineers were found not to be the most effective people at 'process product engineering'. Kahn recommended that in order for the bioengineers to be team leaders in the industrial environment, educational programs have to be re-engineered in such a way that 'the areas of teamwork and the management of people and programs' become an integral part of biomedical engineering training. He added that further training is also needed in the 'technical areas of the interface of body tissues with materials and electrical current'.

In 1981, Potvin *et al.* conducted a quantitative study of biomedical engineering education [17] similar to that reported by Schwartz and Long in 1975 [15]. The study was supported by the Education Committees of four societies: (1) the Biomedical Engineering Division of the American Society of Engineering Education; (2) the IEEE Engineering in Medicine and Biology society; (3) the Biomedical Engineering Society; and (4) the Alliance for Engineering in Medicine and Biology. It consisted of a modified survey questionnaire from the one used in 1974, and was sent to 251 engineering schools in the United States. The modified questionnaire touched on enrollment, courses, and degrees data covering the academic year 1979–1980, and employment data from the academic year 1978–1979. A summary of the major findings of this in-depth survey is given in Table 2. It was noted in this study that the number of schools offering BS, MS, and Ph.D. programs in Biomedical Engineering all increased within the five years preceding the study.

In 1982, White and Plonsey debated whether or not biomedical engineering education produced real engineers [18]. They conducted a study

Table 2. Summary of reported results from Potvin *et al.* (1981) [17]

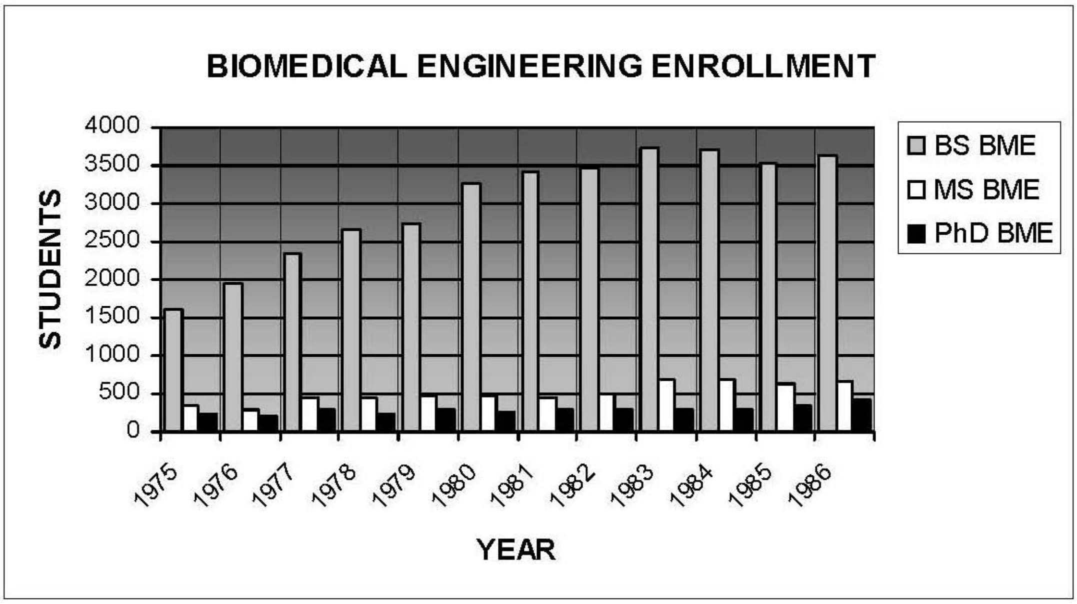
Total U.S engineering schools surveyed (academic year 1979–1980)	**251**
Schools having degree programs in BME	71
Schools having official minor or option programs in BME	35
Schools with no programs or degrees in BME	107
Schools who did not respond	38
BME Programs accredited by the Accreditation Board for Engineering Training/Engineers Council for Professional Development	**22**
Schools awarding degrees in BME	**71**
BS degree	37
MS degree	48
Ph.D. degree	41
Schools offering options or minors in BME in which the student received some other engineering degree	**35**
BS degree	41
MS degree	42
Ph.D. degree	34
BME student enrollment for the 1979–1980 academic year	**4158**
BS degree	2859
MS degree	830
Ph.D. degree	469
BME degrees awarded during the academic year 1978–1979	**820**
BS degree	464
MS degree	249
Ph.D. degree	107
Placement of the BME graduates of the academic year 1978–1979	**630**
Industry	253
Government	23
Academia	35
Hospitals or clinics	66
Medical school	100
BME graduate schools	96
Other graduate or professional schools	57

during the academic year 1980–1981 whereby they surveyed the curricula of 29 institutions of higher learning offering a degree program or an option in Biomedical Engineering. The objective of the study was mainly to quantify the overlap/differences between existing biomedical engineering curricula and the older discipline of electrical engineering. Its hypothesis was to determine the amount of reduction in engineering course work as a result of the inclusion of life sciences within the biomedical engineering programs, and to determine whether the amount of life sciences course work was sufficient. The following conclusions were drawn: (1) 'the amount of life science included in biomedical engineering is adequate to provide for the needs of both students who do not desire further education and those who do'; (2) 'there is indeed enough training in engineering principles to produce highly qualified engineers'; and (3) 'undergraduate biomedical engineering education is both valid and desirable'.

In 1989, Pilkington *et al.* in a research study entitled '*Status and Trends in Biomedical Engineering Education*' reported a steady growth in biomedical engineering since its early years and has that it had gained 'acceptance as body of knowledge soundly based in both the biomedical and engineering disciplines' [4]. The authors expounded on the steady state of the positive correlation between the number of degrees granted and the available number of career opportunities. They also reflected on the increased awareness of contemporary employers pertaining to the evident training and capabilities of biomedical engineers. The authors delineated the actual number of students enrolled both in Engineering and Biomedical Engineering between 1975 and 1986. These results are shown in Fig. 1. They also reported that 18 programs in Biomedical Engineering were accredited by the Accreditation Board for Engineering and Technology, Inc. (ABET, Baltimore, MD, USA). The authors concluded that 'the status of biomedical engineering today can be best described as satisfactory and improving . . . Supply and demand are in good balance, with employment possibilities adequate and of satisfactory quality.'

In 1999, another milestone in Biomedical Engineering Education occurred with a paper published by the *International Journal of Engineering Education*. This special issue consisted of 11 papers as well as the two editorials. According to J. G. Webster, the Guest Editor, 'Many papers in this issue describe alternative approaches to encourage students to find information, develop a systems approach, work with biologists, consider bioethics, develop professionalism, perform design, and develop the skills required to solve biomedical engineering problems' [19].

Two of these papers were found to be relevant to this study and are reviewed here. King took an interesting approach when he attempted to attract the attention of manufacturers of biomedical



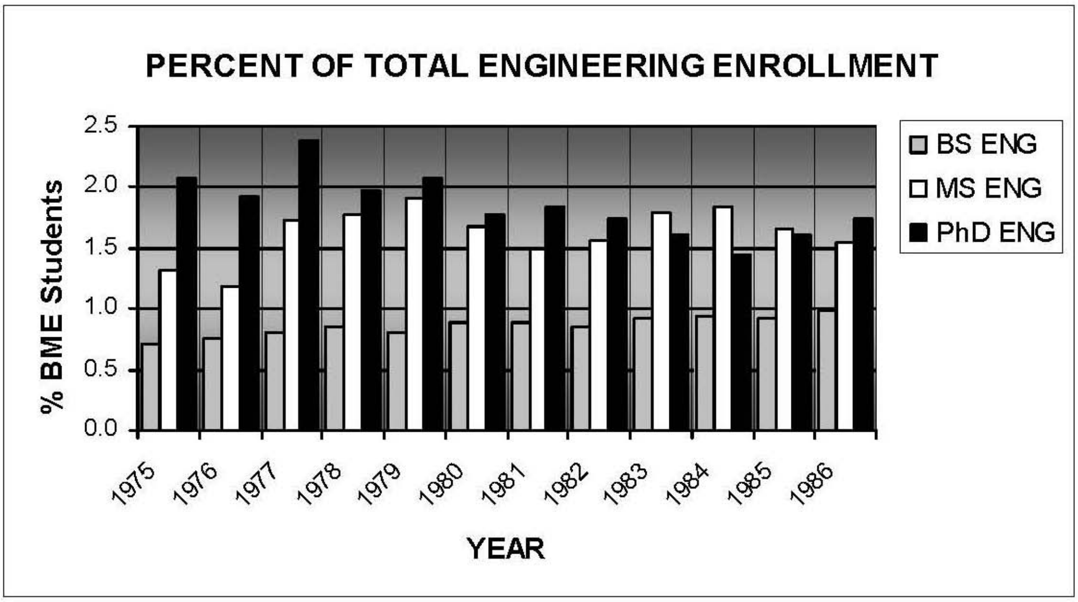


Fig. 1. Top: Number of students enrolled in Biomedical Engineering in the United States between 1975 and 1986 at BS, MS, and Ph.D. levels. Bottom: Percentage of biomedical engineering student enrolled out of the total engineering enrollment in the US between 1975 and 1986 at BS, MS, and Ph.D. levels. (Data compiled from Pilkington *et al.* [4].)

devices and educators in the field to the subject matter of design within undergraduate biomedical engineering curricula in the United States [20]. Sixty nine academic programs in Biomedical Engineering were studied, 21 of which were found to be accredited by ABET; subsequently, King inferred that these accredited programs must have had a significant design content. He further identified 'internships, the new accreditation criteria, and private and governmental support of research and design activities in biomedical engineering programs' as the contemporary phenomena that will influence the future of biomedical engineering programs. As a supportive model in his paper, King used the biomedical engineering curriculum at Vanderbilt University (Nashville, TN, USA). In their paper, Viik and Malmivuo reported the results obtained from a survey investigating the employment situation of biomedical engineering graduates holding a Master of Science degree from the Ragnar Granit Institute at Tampere University of Technology (TUT, Tampere, Finland) [21]. The study surveyed 267 individuals who graduated between 1976 and 1997 and of which 77% responded to the questionnaire. The survey stressed on the following questions: (1) 'How soon after their graduation did engineers acquire a job?'; (2) 'Where did they find a placement and with what type of job description?'; (3) 'How did their job description correspond with their education at TUT?'; and (4) 'Did their job description involve BME?'. The study resulted in the following

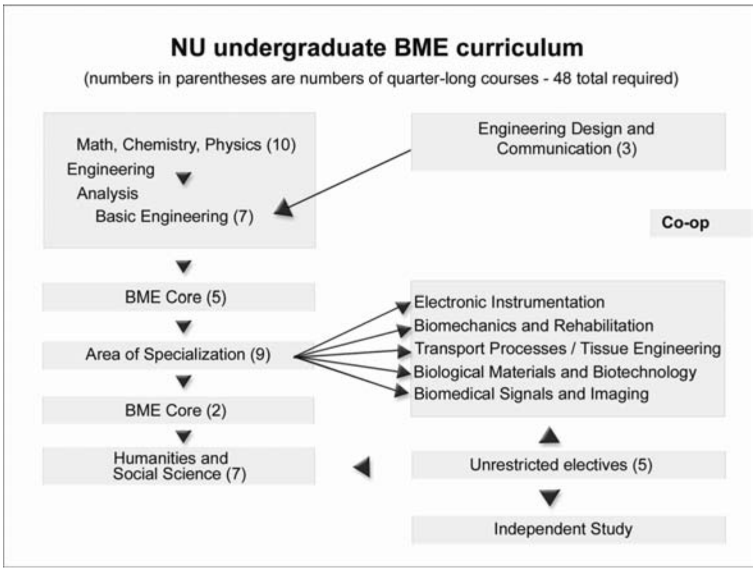


Fig. 2. A sample schematic of the VaNTH-ERC undergraduate curriculum in Biomedical Engineering implemented at Northwestern University (Evanston, IL, USA).

outcomes, respectively: (1) 90% of the respondents found their first job within three months; (2) 95% of the respondents were employed on a full-time basis with 57% located in the Tampere area; (3) 68% of the respondents reported that the tasks of their first job corresponded 'to a large extent' with their education; and (4) 37% of the respondents reported that the relation of job description to biomedical engineering corresponded to being 'fully or almost fully', while 10% corresponded to being 'to some extent'.

Also in 1999, the National Science Foundation (NSF, Arlington, VA, USA) sponsored the development of the Vanderbilt–Northwestern–Texas at Austin–Harvard/MIT Engineering Research Center (VaNTH-ERC, Nashville, TN, USA), whose function is to improve 'the short- and long-term outcomes of biomedical engineering education' at different levels with particular emphasis on undergraduate education [3, 22]. The VaNTH-ERC launched a website to provide a productive medium for sharing ideas about biomedical engineering curricula [23]. Amongst the many important constituents of this website is a listing of '*core content*', rather than '*core courses*', for undergraduate programs in Biomedical Engineering, and recommendations for the creation of biomedical engineering curricula in terms of both content and pedagogy [3].

The VaNTH-ERC for Bioengineering and Educational Technologies recommended that in order to create a curriculum in Bioengineering/Biomedical Engineering, considerations should be made of a number of issues that fall under the following broad categories [23] (1) philosophical underpinnings and assumptions; (2) steps to creating a curriculum; (3) industry requirements for bioengineers; (4) bioengineering content; and (5) basic bioengineering. Of particular interest to this paper is the category '*steps to creating a curriculum*'. In this category the VaNTH-ERC recommended the following: (a) 'Define the type(s) of biomedical engineer that the program will produce and the career paths the program will prepare them for'; and (b) 'Seek multiple perspectives and involve multiple constituencies in the curricular design process. Consider the following as sources of input on curriculum: taxonomy, faculty expertise, students, industry needs, existing programs, and ABET guidelines and outcomes' [23].

To help resolve many of the content issues described in the above five categories, the VaNTH-ERC has created a '*Strawman Curriculum*' for undergraduate biomedical engineering programs [23]. Additionally, they have launched a web-based multi-step survey under the name '*Delphi Study*' to determine the key concepts that should form the foundation or '*core*' of undergraduate biomedical engineering curricula [23,24]. The survey consisted of 80 questions divided into 19 categories that included 'eleven biomedical engineering domains, four biology domains, physiology, engineering design, and mathematical/scientific pre-requisites' [24]. Gatchell *et al.* stated: 'we expect that the results of this survey will aid academia in identifying the fundamental concepts that undergraduate 'biomedical engineers' should know and should facilitate the industrial hiring of a larger percentage of our undergraduates by further establishing the identity of the biomedical engineering field' [24]. Figure 2 shows a schematic view of the undergraduate biomedical engineering curriculum at Northwestern University (Evanston, IL, USA), a member of the VaNTH consortium.

In 2000, the Whitaker Foundation (Arlington, VA, USA) sponsored the first international summit meeting on biomedical engineering education. This meeting congregated important information on active academic programs in Biomedical

Engineering at that time. A number of specific curricula in Biomedical Engineering were subsequently delineated on the Whitaker Foundation summit website [25]. Following its summit meeting, the Whitaker Foundation suggested the following key areas for biomedical engineering curricula [25]:

1. *Basic areas:* biomechanics, bioinstrumentation, biosystems, cell/molecular engineering, and biomaterials.
2. *Advanced areas:* functional genomics, biomems (biomicro-electro-mechanical systems), cell/tissue engineering, computational biology, and bioimaging.

Katona, commenting on the outcomes of the summit meeting, stated that 'the participants concluded that developing a single, 'optimal' program is neither possible nor desirable. Programs need to define their own objectives, taking into account current and planned institutional strengths, then these goals should be pursued vigorously and imaginatively. Most agree that programs must have rigor both in engineering and the life sciences and that integrating the two components must occur throughout the curriculum' [10].

In 2002, Harris *et al.* reviewed the recent advances within learning sciences and learning technologies and their respective roles in biomedical engineering education [2]. The authors identified that challenges facing biomedical engineering education are targeted at all components of the educational process, namely faculty, students, and employers of graduates. They asserted that instructional paradigms in Biomedical Engineering could be re-assessed according to the '*How People Learn*' framework provided by the new advances in the learning sciences. In their study, the authors demonstrated that learning environments should be: (1) '*learner centered* in the sense that they take into account the knowledge, skills, preconceptions, and learning styles of the learners'; (2) '*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'; (3) '*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'; and (4) '*community centered* in the sense that they foster norms that encourage students to learn from one another, plus encourage faculty to do likewise.' They proceeded to say that learning technologies could optimize the genesis of this environment. The study concluded that evolutions in learning sciences and learning technologies together with reform in engineering education are to be considered as advantages that educators in Biomedical Engineering could benefit from in designing and implementing new learning systems. It is worth noting that the paper reported that there were 21 undergraduate programs in Biomedical Engineering within the United States accredited by ABET.

In 2003, the IEEE Engineering in Medicine and Biology Magazine, under the topic section '*New Directions in BME Education*', hosted 16 articles; from which seven were sampled to be included in this review. In his paper, Linsenmeier focused on the means of addressing the needs of the industry as well as the extent to which a common undergraduate curriculum in Biomedical Engineering can and should exist [26]. Specifically, the author stated that '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'. He added that the main thrust should therefore be on preparation for industry and consequently raised the following four questions: (1) 'What perception does industry have of biomedical engineers?'; (2) 'What are the needs of industry?'; (3) 'What niches will biomedical engineers occupy at the BS level?'; and (4) 'Which industries should we consider in our analysis of needs?' Subsequently, the author reported that according to the VaNTH curriculum project, biomedical engineering programs should concur at least on what biomedical engineers should know and not necessarily on the whole curriculum. He concluded 'We are seeking a core set of knowledge and skills that we call 'key content'.' The paper reported that 24 programs in biomedical engineering were accredited by ABET at the time.

In another paper, Brophy hypothesized that 'Innovations in learning sciences and technology are opening new opportunities for designing and implementing effective learning materials that can be shared between bioengineering instructors' [27]. The author reported that the VaNTH-ERC was investigating, along the same lines, methods to design and validate learning materials for bioengineering education and putting together a technological foundation that supports the reusability of these materials based on sound pedagogical principles. He added that, through the formulation of specialized design teams for redesigning bioengineering education, the VaNTH has defined a design process that benefited from the current theories of learning sciences and best practices in engineering education. He elaborated that the multidisciplinary team consisted of 'domain experts, learning scientists, assessment experts, and technology experts'. Subsequently, the author, referring to the design teams, stated: 'Their decisions about what and how to teach their content has been guided by a learning cycle to support inquiry learning and the how people learn (HPL) framework, which identifies important principles of effective learning environments'. Concurrently, the author emphasized the use of challenge-based instruction (CBI) in organizing course content.

Brophy explained that together, 'The HPL framework and CBI provide structure for categorizing the important features for an engineering learning environment'. He added that the eventual success of the learning environment will depend on a series of factors that 'define key steps in planning a module of instruction and an entire course that uses a collection of challenges and learning activities.' These factors were: (1) 'identifying course-level learning objectives'; (2) 'identifying unit-level learning objectives'; (3) 'identifying and prioritizing course content to meet these goals'; (4) 'defining assessment items to verify achievement of these goals'; (5) 'defining effective challenges that motive students and set up meaningful inquiry that meet the learning objectives'; and (6) 'defining learning materials and activities that support learning with understanding.'

It is worth noting that the HPL framework is described in '*How People Learn: Brain, Mind, Experience, and School*', a manuscript by the National Research Council (National Academy of Sciences, Washington, DC, USA) [28]. Cordray *et al.*, in their paper, described the application of a 'counterfactual model of causal analysis', which has been used to assess the 'value added' for the project-level assessment and evaluation activities made by the VaNTH [22]. The authors concluded that: (1) 'Based on a counterfactual model of causal analysis, VaNTH investigators have been encouraged to use experimental and quasi-experimental research designs to estimate the 'value added' for their innovations'; (2) 'By applying the logic, principles, and criteria of a counterfactual causal model, as opposed to a 'cookbook' application of designs and statistical procedures, VaNTH investigators have begun to develop a firm knowledge base about the relative effectiveness of their HPL-inspired innovations'; (3) 'It is possible to assess and evaluate, in a quantitative way, the relative effects of educational innovations in engineering courses'; (4) 'A broader assessment of the HPL model underlying VaNTH can be undertaken by systematically looking across studies within VaNTH'; and (5) 'By implication, the knowledge gained about engineering education from assessment and evaluation efforts within VaNTH should be much greater than the sum of its parts.' Riesbeck *et al.* reported that numerous learning technologies have been developed within the VaNTH-ERC for Bioengineering Educational Technologies to uphold the use of 'Web-based interactive environments' that encourage critical reasoning skills in engineering learning contexts [29]. Within this framework, the authors expounded on two applied technologies: the Indie and SASK tools. The Indie tools, whose name is an acronym for investigate and decide, 'are for authoring and delivering challenge-based scenarios where learners have to investigate a situation, perform (simulated) experiments, and use the resulting data to argue for and against possible hypotheses and courses of action.' While the latter tools, whose name is an acronym for 'Socratic ask', 'are for authoring and delivering question-driven Socratic dialogs to foster critical reflection by learners engaged in a problem-solving challenge.' These tools were developed, using a bottom-up design approach, to support 'challenge-based learning activities' that have proven to be 'effective for long-term learning'.

Fries described a 'Win–Win–Win' relationship in Biomedical Engineering, whereby the beneficiaries are the students, the university, and the industry [30]. His paper delineated the involvement of the industry in senior biomedical engineering design courses and summarized a four-year partnership among Datex-Ohmeda (Louisville, CO, USA), Vanderbilt University (Nashville, TN, USA), and VaNTH-ERC, in addition to the cooperative (co-op) and summer internship programs with Marquette University (Milwaukee, WI, USA) and the University of Wisconsin (Madison, WI, USA). Fries described the benefits of such an endeavor as follows: *Students* (1) 'gain the knowledge they will need to succeed in industry after graduation'; (2) 'get the experience of working within an industrial product development program'; (3) 'use the knowledge they have gained at the university in a real-world situation'; and (4) 'get paid for working as co-ops or interns'. *The university* (1) 'learns more about how the industrial product development process works'; (2) 'learns what topics are important to that product development process'; (3) 'gets active participation by industrial personnel'; and (4) 'receives donations in the form of time, equipment, and money'. *Industry has* (1) 'input on what students are learning and how that will prepare them for their potential positions'; (2) 'the opportunity to identify students as potential employees'; (3) 'students working on projects that the company can use in their own product development'; and (4) 'students working for them for a short time to assist in their product development'. Fries concluded his paper by hypothesizing that the involvement of biomedical companies and institutions of higher learning in this kind of program could yield a significant improvement in Biomedical Engineering as well as in healthcare.

Another paper, by Waples and Ropella, addressed the *University–Industry Partnerships in Biomedical Engineering* [31]. The authors reported that with the aid of a 1995 Whitaker Foundation Industrial Internship Grant, Marquette University was able to establish the largest *cooperative education* and *industrial internship* program in Biomedical Engineering within the United States. Consequently, the focus of their paper was to describe the crucial activities required to establish and maintain such a prosperous program. The authors stated that three fundamental elements were required to establish this endeavor: (1) 'a professional development process weaved into a unique freshman/sophomore curriculum'; (2) 'proactive recruitment of cooperative and internship opportunities'; and (3) 'an infrastructure to sustain the university–industry partnerships and monitor the experiences of both students and industry participants'. Four main outcomes were reported in this study: (1) 'The investment of personnel, time, and money for the past eight years has produced industrial partnerships with over 30 companies and additional yearly interactions with over 175 companies throughout the United States'; (2) 'The return of our investment has been a continued increase in the students and employers participating in the cooperation program'; (3) 'Our students have experienced greater success in full-time placement based on the increased participation with employers recruiting at Marquette University'; and (4) 'We have benefited from increased enrollments in our undergraduate program'. Moreover, the paper described the cumulative benefits to all stakeholders by stating that: *Participating students* (1) 'work as engineering professionals'; (2) 'gain valuable engineering and business experience'; (3) 'apply engineering concepts to real-world problems'; and (4) 'tend to be more focused on their career choices after participating in a cooperation or internship opportunity'. *Employers (1)* 'have the opportunity to train potential long-term employees'; (2) 'capture the attention of motivated, talented biomedical engineers'; (3) 'obtain visibility at the university'; and (4) 'ultimately lower their turnover and training costs'. *The Biomedical Engineering Department* (1) 'benefits from industrial partnerships through increased student satisfaction'; (2) 'improved student training'; (3) 'novel education programs'; (4) 'job placement for graduates'; and (5) 'research collaboration.'

The last of these sampled papers, written by Enderle *et al.*, discussed '*The ABCs of Preparing for ABET*'. This paper, which was written by fully trained ABET evaluators, offered guidelines for planning, implementing, and accrediting biomedical engineering programs [32]. The authors noted that 'ABET, Inc. is recognized by the U.S. Government as the accreditation organization for college and university programs in applied sciences, computing, engineering, and technology'. They proceeded by stating that the main functions of ABET are to: (1) set the goals and objectives for accreditation; (2) evaluate the process; and (3) constantly release improvement guidelines. They added that the student, faculty, facilities, institutional support, and financial resources are the bases for program evaluation. The authors reported that the new program review process of ABET, known as 'Engineering Criteria 2000—EC2000' or simply 'Engineering Criteria—EC', has created 'a change from a prescriptive evaluation to one based on program-defined missions and objectives with an emphasis on outcomes'. Subsequently, all pertaining programs aiming for accreditation had to implement this new EC as of the year 2001. Interestingly, Enderle *et al.* recommended that 'Since the ABET criteria provide only a minimum set of requirements, 'Biomedical Engineering' programs should not use this as a target but rather set their goals higher by including state-of-the-art and real-world experiences that enrich the curriculum' [32]. Details about the ABET's 'EC2000 Criterion 3—Program Outcomes' and 'Program Criteria' pertaining to bioengineering and biomedical engineering are provided below.

In 2005, the Whitaker Foundation instantiated its second and last international summit meeting on biomedical engineering education before the Foundation came to an official close in 2006. In concert with the first meeting, the second aimed at helping universities to design and modify their programs in Biomedical Engineering so as to meet future challenges [25]. The two complementary educational philosophies formed the pillars for the two meetings: one made by the Whitaker Foundation, and the other by ABET. Both philosophies are reported:

Whitaker curriculum philosophy [25]

1. A thorough understanding of the life sciences, with the life sciences a critical component of the curriculum
2. Mastery of advanced engineering tools and approaches
3. Familiarity with the unique problems of making and interpreting quantitative measurements in living systems
4. The ability to use modeling techniques as a tool for integrating knowledge
5. The ability to formulate and solve problems with medical relevance, including the design of devices, systems, and processes to improve human health.

ABET curriculum philosophy [25, 33]

As a meeting concerned with professional education, the premise is that bioengineering and biomedical engineering curricula for bachelor's degree granting programs will be accredited. ABET, the accrediting agency, has promulgated criteria that must be satisfied for the educational program to receive accreditation. Specifically, bioengineering and biomedical engineering programs must demonstrate that their graduates have:

a) an ability to apply knowledge of mathematics, science, and engineering;
b) an ability to design and conduct experiments, as well as to analyze and interpret data;
c) an ability to design a system, component, or process to meet desired needs;
d) an ability to function on multi-disciplinary teams;
e) an ability to identify, formulate, and solve engineering problems;
f) an understanding of professional and ethical responsibility;
g) an ability to communicate effectively;
h) the broad education necessary to understand the impact of engineering solutions in a global and societal context;
i) a recognition of the need for, and an ability to engage in, life-long learning;

j) a knowledge of contemporary issues;
k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice; and, specific to bioengineering and biomedical engineering,
l) an understanding of biology and physiology, and the capability to apply advanced mathematics (including differential equations and statistics), science, and engineering to solve the problems at the interface of engineering and biology;
m) the ability to make measurements on and interpret data from living systems, addressing the problems associated with the interaction between living and non-living materials and systems'.

Furthermore, the criteria indicate that:

Students must be prepared for engineering practice through a curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating engineering standards and realistic constraints that include most of the following considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social and political. [25].

It is worth noting that outcomes a–k constitute 'Criterion 3—Program Outcomes' of the EC2000 of ABET, which was described earlier, while outcomes l–m constitute the 'Program Criteria for Bioengineering and Biomedical Engineering and Similarly Named Engineering Programs'; the latter, at first, states that '*The structure of the curriculum must provide both breadth and depth across the range of engineering topics implied by the title of the program*' [33].

Katona, in 2002, provided a historical review of the Whitaker Foundation [10]. He also described its goals and some of its programs and speculated about the future of Biomedical Engineering following the closure of this Foundation in 2006. Katona reported that since its inauguration in 1976, the Whitaker Foundation granted more than 700 million US$ and he expected that an additional 100 million US$ be granted before the closure of the Foundation. The author delineated the following contributions of the Whitaker Foundation: (1) support to over 1300 investigators through the Biomedical Engineering Research Grant program; (2) 30–40 new doctoral fellowships were typically granted every year; and (3) a total of 75 institutions have received awards ranging from 750 000 US$ to 18m US$. Katona elaborated that the increased spending level from 1991 till 2003, the year that marked the last of the 'multiyear awards', has caused acceleration in the formation of formal educational programs at universities in addition to constructing new facilities. He concluded his paper by answering the question 'whether the field of biomedical engineering will continue to prosper after Whitaker funding ceases' with a strong affirmative.

In 2006, Linsenmeier and Gatchell in their paper entitled '*Core Elements of an Undergraduate Biomedical Engineering Curriculum—State of the Art and Recommendations*' reported that the number of US undergraduate programs in Biomedical Engineering and Bioengineering accredited by ABET has reached 37 as of Spring 2006 [34]. The objective of their paper, using both the Delphi approach and the ABET accredited programs, was 'to identify elements of undergraduate biomedical engineering and bioengineering curriculum that should be common across universities'. The study outcomes confirmed that no two programs were identical; however, they revealed an overlap of 75% in certain required courses among the studied programs. The overlapping courses were functionally 'regarded as the core' at that time. Moreover, the data from the Delphi study implied the addition of a few courses to that core, leaving 18.2 ± 9.6 credit hours to be added for specialization courses as exercised by the accredited programs. The authors concluded by recommending the following: (1) 'We imposed a limit of 78 credit hours for the core, allowing 18 hours of flexibility in specialization courses'; (2) 'Engineering, math and science then comprise 96 credit hours, three quarters of a typical 128 hour curriculum'; and (3) 'Within the 78 units we also recommend two of the following three courses: signal analysis, organic chemistry, and thermodynamics. We prefer to recommend all three'.

In 2007, Nagel *et al.* wrote a comprehensive manuscript about the medical and biological engineering and science in the higher educational system within Europe [35]. They started with an elucidation of the Bologna Declaration, signed in 1999, and its objectives, which have led to the Bologna Process following their implementation. Among these objectives was the demand for the establishment of a European Higher Education Area (EHEA). It is worth noting that, as of 2004, the number of European countries participating in the Bologna Process reached 45 at a time when the European Union (EU) encompassed 25 member countries. The authors reported that, emanating from the EU list of priorities, the Bologna movement has motivated the European Medical and Biological Engineering and Science (MBES) community to establish their 'Higher Education Area' by (1) 'harmonizing the educational programs'; (2) 'specifying minimum qualifications'; and (3) 'establishing criteria for an efficient quality control of education, training, and lifelong learning'. These guidelines were adopted by MBES and became their target objectives, namely to 'establish a general European consensus on guidelines for the harmonization and accreditation of high-quality MBES programs and for the certification and continuing education of professionals working in the healthcare systems'. Subsequently, the authors reported that more that 200 institutions of higher learning in

Europe offer academic programs in MBES at the bachelor, masters, and doctoral levels. The authors drew attention to the lack of international coordination pertaining to 'contents and required outcome qualifications'.

However, they reported that despite the differing educational environments, the interactions in biomedical engineering education between Europe and the United States have been strong. They expounded that the universities in the United States work in autonomy, taking full control of their higher educational system, while in some European countries it is the government. They also highlighted some of the major deficits within the European higher educational system by adding that Europe has not had the chance to benefit from funds, such as those provided by the Whitaker Foundation, to establish new biomedical engineering programs and research; and that Europe has not been endowed with a generally accepted accreditation agency, similar to ABET, that would take charge of the many facets of quality assurance in higher education. The authors then stated that starting from 1999 a Europe-wide consortium has been (1) 'engaged in projects aiming at creating a comprehensive survey of the status of MBES education and research in Europe'; (2) 'charting the MBES community'; (3) 'developing recommendations on harmonized MBES education, training, and certification'; and (4) 'establishing criteria for the accreditation of MBES programs in Europe'. Accordingly, in 2004, a Europe-wide participation project under the name 'BIOMEDEA' was set up in order to achieve the above objectives. The authors reported that BIOMEDEA, mainly sponsored by the International Federation for Medical and Biological Engineering (IFMBE, Zagreb, Croatia), is progressing in a productive manner and that 80 European academic institutions have participated in the three meeting that have taken place thus far. Subsequently, the authors reported that there have been agreements on (1) the 'Criteria and Guidelines for the Accreditation of Biomedical Engineering Programs in Europe' and (2) a 'European Protocol for the Training of Clinical Engineers.' Finally, the authors concluded that 'The evolving EHEA will substantially influence the development of educational aspects of medical and biological engineering and sciences.'

BIOENGINEERING AND BIOMEDICAL ENGINEERING

Subsequent to this extensive literature review, it is imperative that comprehensive and proper definitions of Bioengineering and Biomedical Engineering be well formulated and their key divisions be properly highlighted and described. The definitions of the two fields have been compiled from professional organizations that have global recognition.

Definitions

The working definition of Bioengineering according to the National Institutes of Health (NIH, Bethesda, MD, USA) is [36]: 'Bioengineering integrates physical, chemical, or mathematical sciences and engineering principles for the study of biology, medicine, behavior, or health. It advances fundamental concepts, creates knowledge for 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.'

The Whitaker Foundation defined Biomedical Engineering as [37]: '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.'

In addition, the Biomedical Engineering Society (BMES, Landover, MD, USA) provided the following definition for the biomedical engineer [38]: '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.'

Key divisions

According to Bronzino, Biomedical Engineering may be classified into 15 key divisions [8, 39], where almost any of these subdivisions could be considered as a field of study in its own right. These interconnected, and at times overlapping, constituents are mainly referenced in [38–41], and are described here with some modifications and the addition of Bioelectromagnetism [42] and Bioethics [43–45]:

1. *Bioelectromagnetism* is a division of Bioengineering/Biomedical Engineering that investi-

gates the electric, electromagnetic, and magnetic phenomena arising in biological tissues, thence resulting in the emergence of three new areas, namely, bioelectric, bioelectromagnetic, and biomagnetic phenomena. These areas encompass the study of: the behavior of excitable tissue, the electric currents and potentials in the volume conductor, the magnetic field at and beyond the body, the response of excitable cells to electric and magnetic field stimulation, and the intrinsic electric and magnetic properties of the tissue. The fact that bioelectromagnetism employs measurement and stimulation methodology it makes it an interdisciplinary field that links life sciences with the physical and engineering sciences. Subsequently, this division has special interest in biophysics, bioengineering, biotechnology, medical electronics, and medical physics [42].

2. *Bioethics* addresses the ethical issues posed by developments in the biological sciences, and their application to medical practice. As stated by Potter, Bioethics emphasizes 'the two most important ingredients in achieving the new wisdom that is so desperately needed: biological knowledge and human values' [43, 44]. In other words, bioethics recognizes the moral aspects related to applications and experiments on human, social, environmental, and global concerns. According to Veatch, the four levels of 'Moral Discourse' in ascending order are: 'Cases (Casuistry), Rules and Rights (Code of Ethics), Normative Ethics, and Metaethics' [45].
3. *Biomaterials* involves the research and design of safe and reliable synthetic materials that can intimately contact living systems and tissues in a physiologically acceptable and pharmacologically inert way; that is, these materials have to be chemically inert, non-thrombogenic, non-toxic, and non-carcinogenic. Additional requirements are adequate mechanical strength and fatigue life, proper weight and density, and use in reproducible and cost-effective large-scale fabrication [40]. There are four main classes of biomaterials: metals, ceramics, polymers, and composites. It is worth noting that various biological materials, such as bone and skin, are naturally occurring composite biomaterials.
4. *Biomechanics* applies the principles of classical mechanics to solve related problems in biology and medicine through the determination of time and space characteristics of biological solids, fluids, and viscoelastic materials in response to imposed systems of internal and external forces. Additionally, biomechanics enhances the knowledge about the structure and function of various physiological systems in both health and disease, as well as in providing quantifiable cues about the mechanisms of failure or injury needed to understand and modify the environment of the targeted population [40].
5. *Biomedical Instrumentation* is involved in the design, development, and utilization of devices to monitor and measure physiological variables and parameters by applying interdisciplinary engineering principles. Biomedical instrumentation includes equipment used to improve or maintain the health and well-being of a patient. This division also comprises the development of biomedical sensors [40].
6. *Biomedical Sensors*, also known as *biosensors*, are devices that detect and convert biologically significant signals into electrical, optical, or physical ones. Such sensors carry diagnostic, therapeutic, and monitoring applications. They are also used in biomedical research and development [40].
7. *Bionanotechnology* is a rapidly emerging division of Bioengineering/Biomedical Engineering emanating from the more global area of nanotechnology. The latter provides the ability to build and shape matter one atom at a time with a *nano* scale that signifies one part out of a billion. Accordingly, nanobiotechnology is concerned with biologically natural or synthetic structures, devices, and phenomena that are on a scale between atomic distances and the wavelength of visible light. Typical applications of bionanotechnology include: (1) the creation of targeted nanomachines for use in nanomedicine; (2) the construction of DNA computers; (3) the development of biosensors; (4) the production of novel biomaterials using self-assembly; (5) the harnessing of molecular motors; and (6) the development of hybrids of bionanomachinery with inorganic materials [46].
8. *Biotechnology*, or *biological technology*, is recognized as having immeasurable potential for promoting human well-being through fulfilling critical needs for food, agriculture, and healthcare; hence, the added attention to this subdivision herein. The United Nations Convention on Biological Diversity provided the following definition [47]: 'Biotechnology means any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use.' Moreover, the Cartagena Protocol on Biosafety recognized modern Biotechnology as 'having a great potential for the promotion of human well-being, particularly in meeting critical needs for food, agriculture and health care.' This Protocol adds the following definition of the term: 'a) In vitro nucleic acid techniques, including recombinant deoxyribonucleic acid (DNA) and direct injection of nucleic acid into cells or organelles, or b) fusion of cells beyond the taxonomic family, that overcome natural physiological reproductive or recombination barriers and that are not techniques used in traditional breeding and selection' [48].

Generally speaking, until the end of the last millennium biotechnology was not considered a discipline but rather a collection of procedures and techniques whereby a scientist or an engineer attempted to create or modify biological organisms for the benefit of humanity [40]. These attempts have evolved throughout the millennia from a traditional biotechnology to an ever developing modern one. They include, in chronological order, microbial fermentation, biological nitrogen fixation, plant tissue culture, embryo transfer of animals, clonal and polyclonal antibody production, recombinant DNA technology, genetic engineering of plants, genetic engineering of animals, and genomics [49]. Today, it is debated that biotechnology has become a discipline by itself, one that a student can attain a three-level-degree (Bachelor/Masters/Doctoral) in the stated field.

Four basic key processes of biotechnology governing its wide spectrum are presented next. Nevertheless, it is worth the reader pursuing other key processes in this spectrum, namely *yellow*, *brown*, *dark*, *purple*, and *gold*, in depth.

i) *White biotechnology*, also recognized as *grey biotechnology*, applies to industrial processes. It makes use of living cellular products such as moulds, yeast, and bacteria, as well as enzymes to produce goods and services. Examples include the production of antibiotics, vitamins, vaccines, and proteins for medical use. It is hoped that white biotechnology would reduce pollution and waste; decrease the use of energy, raw materials, and water; realize better quality food products; and create new materials and biofuels from waste products.
ii) *Red biotechnology*, also known as *healthcare biotechnology*, applies to medical processes. It plays a significant role in contemporary production of medicaments and vaccines, as well as in the emergence of stem-cell and gene therapies. It is expected that this biotechnology would allow the development of innovative techniques to the prevention, diagnosis, treatment, and cure of existing incurable diseases. Examples include antibiotics produced by especially designed organisms and genetic cures engineered through genomic manipulation.
iii) *Green biotechnology*, also known as *plant biotechnology*, applies to agricultural processes. One of the attempts of this biotechnology is to produce environmentally friendly solutions not plausibly attained by conventional industrial agriculture. A potential aim of green biotechnology is to introduce foreign genes into economically vital plant species, resulting in crop improvement and the production of new products in plants. Today, plant biotechnology twirls around three major areas: plant tissue culture, plant genetic engineering, and plant molecular marker-assisted breeding.
iv) *Blue biotechnology* applies to coastal, marine, and aquatic processes. Its main objective is to explore the genetic diversity of these ecosystems. Examples of this biotechnology include the use of certain bioluminescent micro-organisms that luminesce in sea water at night to identify toxin levels within minutes. Another contemplated prospective application is developing aquaculture fish health, breeding, and feeding.

9. *Clinical Engineering* is specialized in the support and advancement of patient care by applying engineering and managerial skills to healthcare technology. The clinical engineer is a member of the healthcare team within a hospital or a clinic. Clinical engineering practices include health technology management, safety, medical device service, technology application, information technology, education and training, research and development, clinical facilities, and standards and regulations [40, 50].
10. *Medical and Bioinformatics* are two different multidisciplinary fields, although they share the same methodology applied to their underlying information systems. Medical informatics is concerned with the interpretation of patient-related data and assisting in clinical decision making [40]. On the other hand, bioinformatics involves the mathematical, statistical, and computational analyses of biomolecular data. The different methods utilized in medical informatics and bioinformatics include systems engineering, expert systems, artificial intelligence, neural networks, database design, and applied mathematics and statistics.
11. *Medical and Biological Analysis*, also known as *biomedical signal analysis*, is concerned with the processing of biomedical signals so that the physiological parts of the signals are extracted. Processing involves noise-reduction enhancement techniques as well as information-disclosure transformation techniques. 'Sources of biomedical signals include: (1) bioelectrical signals generated by nerve cells and muscle cells; (2) bioimpedance signals from the impedance of tissue; (3) bioacoustic signals from the flow of blood and air and sounds in the digestive tract, the joints, and the contracting muscles; (4) biomagnetic signals from various organs, such as the brain and the heart; (5) biomechanical signals resulting from mechanical function, such as motion, displacement, pressure, tension, and flow; (6) biochemical signals arising from chemical measurements; and 7) biooptical signals by both natural and induced optical functions' [40].
12. *Medical Imaging* provides graphical displays of anatomical structures and physiological functions. Examples of conventional medical ima-

ging modalities include: endoscopy, X-rays, magnetic resonance imaging (MRI), positron emission tomography (PET), single-photon emission computed tomography (SPECT), ultrasound, and computed tomography (CT). Magnetic resonance microscopy is a recent extension of MRI used in histological studies, toxicological studies, and developmental biology. It provides non-invasive and non-destructive three-dimensional high-resolution images of biological samples. Virtual reality is another modern modality of medical imaging that plays an important role in the studies of anatomy and physiology, virtual surgeries, telemedicine, and telesurgery [40].

13. *Neural Engineering* is an emerging division of Bioengineering/Biomedical Engineering emphasizing research through the use of engineering techniques so as to investigate the function and to manipulate the behavior of the central or peripheral nervous system. This division depends on experimental and computational neuroscience, clinical neurology, electrical engineering, and signal processing of living neural tissue. Neural engineering also relies on robotics, computer engineering, tissue engineering, materials science, and nanotechnology. Robinson provided a more formal and comprehensive definition of neural engineering, which was compiled from scientific, technological, clinical, and end-user perspectives. He stated that 'Neural Engineering is the synergistic and highly interdisciplinary marriage of the neuroscience disciplines and those of engineering and computer science. It seeks to tap directly or indirectly into the nervous system to obtain sensory or command and control signals, to activate outgoing neural signals, and/or to influence processing within the central nervous system. Neural Engineering also, seeks methods to restore lost or compromised neurological function. Neural Engineering is involved in designing, analyzing, and testing functional interfaces between neuroprosthetic systems and neurobiological systems. Neural Engineering also tests all of these components as systems, both in an engineering sense and in a physiological sense. Neural Engineering's design goals, achievable through rigorous *in vitro*, *in vivo* and clinical research, advance the understanding of sensorimotor neuroscience; and produce neural prostheses that are reliable, robust, safe, functionally transparent and cosmetically acceptable' [51].
14. *Physiological Modeling, Simulation, and Control* make use of computer simulations to develop an understanding of physiological relationships. *Physiological modeling* helps in: (1) biomedical research and development by validating hypotheses or highlighting areas for further study; (2) the refinement of teaching and training methods used in medical schools; and (3) clinical applications in such areas as diagnosis, determination of drug regimens, or design of biomedical devices that include prostheses or drug delivery systems. *Physiological simulation*, unlike modeling, aims at reproducing the experimental data without identifying the mechanisms responsible for the experimental observations [40]. In *physiological control*, control theory is used in the analysis of physiological problems and the design of related strategic solutions by applying classical control, state-space control, fuzzy control, and adaptive control methods among others.
15. *Prosthetic-Orthotic Devices and Artificial Organs*, or *rehabilitation technology*, is that segment of assistive technology designed specifically to rehabilitate individuals with certain disabilities in order to improve their existing limitations, whether temporarily or permanently. Conventionally, *orthotics* are devices that augment the function of an extremity, whereas *prosthetics* replace a body part both structurally and functionally. When the prosthetic device replaces all or part of an organ, it is referred to as an *artificial organ* that carries slight resemblance to its natural counterpart [40].
16. *Rehabilitation Engineering* is the application of science and technology to alleviate the severity of the handicaps in disabled individuals, thereby (1) restoring the partial or complete ability to perform daily-living activities and (2) helping in retaining this ability. In order to achieve the above goals, rehabilitation engineering usually involves the design and development of therapeutic and rehabilitation devices and procedures taking into consideration the biological, physiological, psychological, social, and financial aspects of the rehabilitated individual [40].
17. *Tissue engineering* is the study of tissue dynamics that coordinate tissue repair, replacement, and reconstruction. This division of Bioengineering/Biomedical Engineering combines basic biological sciences, engineering fundamentals, clinical aspects, and biotechnology to produce procedures and therapies in which biological cells act as therapeutic agents [40, 52]. Tissue engineering may be further divided into two main categories [40]:

    i) *Ex vivo* or *in vitro* methods entail the use of bio-artificial tissues that are hybrids of synthetic and living material. For example, a typical use of *ex vivo* or *in vitro* tissue engineering is in organ replacement in lieu of an organ transplant.
    ii) *In vivo* applications, attempt to modify the growth and function of cells. For instance, a typical *in vivo* application would use implanted polymeric tubes to promote nerve regeneration by reconnecting damaged nerves in the peripheral nervous system.

CAREER DEVELOPMENT

Background

The field of Bioengineering/Biomedical Engineering is continuously changing due to the leaping advancements in technology. There is no doubt that new areas in this field are to be introduced to the well-established divisions described earlier; a déjà vu fact that has been emphasized by Harris *et al.* who drew attention to the fact that there have been numerous 'paradigm shifts' spanning from 1975 to 1995 within biology, medicine, and engineering [2]. The authors added that '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' [2].

Even though the literature holds considerable advice pertaining to career development in Bioengineering/Biomedical Engineering [2, 9–11, 14, 15, 21, 24]; however, they are non-explicit, fragmented, and most often have to be inferred and read between the lines. Furthermore, it is impractical to expect a prospective college student to perform an intensive literature survey in order to assemble non-all-inclusive career guidelines. Therefore, this paper compiles a comprehensive set of career guidelines and assembles them into a road map to be pursued by a prospective student who is aiming at planning and designing a career in this vital domain. These guidelines stem from the author's expertise, in-depth knowledge of the literature, and field of experience as a founding chair of a regional premier comprehensive undergraduate biomedical engineering curriculum in Lebanon in 2002 [5]. Supplementary information about career planning and designing in Bioengineering/Biomedical Engineering can be obtained from the Biomedical Engineering Society (Landover, MD, USA) [38] and the IEEE Engineering in Medicine and Biology Society (Piscataway, NJ, USA) [53].

It is worth noting that career development in Bioengineering/Biomedical Engineering starts with a passion nurtured with a decisive aptitude, augmented with a keen vision, strategic planning, and careful design, which are fulfilled by an enrollment in a solid curriculum, to secure vocational success and prosperity.

Recommendations

The roadmap toward a successful career in Bioengineering/Biomedical Engineering is normally an intricate one, interwoven with inherent challenges. Yet, the following set of over twenty recommendations, to individuals seeking a career in these domains, may smooth the path:

1. Have a passion for the field and an objective assessment of your capabilities.
2. Determine your goals and objectives, taking into consideration the advancements of the field in the next decades.
3. Develop a comprehensive understanding of the field and its key divisions.
4. Work to attain a professional aptitude built upon firm pillars: integrity, authenticity, seriousness, commitment, punctuality, reliability, responsibility, professionalism, and motivation.
5. Enroll in a competitive undergraduate program in Bioengineering/Biomedical Engineering; whether a *track option* emphasizing one or more related subdivisions or a *comprehensive* program. The difference between a track option and a comprehensive program is explained below.
6. Be careful, when choosing a track option curriculum, that it will be commensurate with job opportunities within the region ion which you plan to settle. Certain regions might have no opportunities in some tracks.
7. Choose a program that integrates courses in biomedical sciences within the bioengineering/biomedical engineering curriculum [10, 11, 15, 25]. Biomedical sciences courses include, but are not limited to, cellular and molecular biology, general and organic chemistry, biochemistry, and anatomy and physiology.
8. Choose a curriculum that deploys the bioengineering/biomedical engineering program at both levels of education: *theoretical* and *applied* [2]. Applied education encompasses design courses, research and development, laboratory courses, knowledge of manufacturing issues, and use of simulation and modeling techniques [25, 33].
9. Develop an understanding of professional and ethical responsibilities [25, 33].
10. Strengthen your oral and written communication skills in more than one language [25, 33]; especially in English, since it is becoming the dominant international language of communication [21].
11. Challenge your critical thinking abilities and work on augmenting your analytic and problem solving skills [25, 33].
12. Take one or more course(s) in management of physical, human, and financial resources. These are vital for enhancing one's ability to deal effectively with vocational daily life challenges.
13. Nurture your abilities to work with teams and making group decisions. Be prepared to function in a multi-disciplinary team [21, 25, 33]. Harmon speculated that 'In all likelihood most biomedical engineers of the future will be modified interdisciplinary hybrids' [9].
14. Take part in practical bioengineering/biomedical engineering training, cooperative educational training, or industrial internship, in an area pertaining to your choice of specialization [15, 20, 30, 31]. Many academic programs mandate this training as a partial requirement towards the fulfillment of the undergraduate degree.

15. Attend relevant summer workshops and, wherever possible, do volunteer work in pertinent areas of healthcare.
16. Choose the right technical elective courses, while pursuing your undergraduate degree, as a prelude to identifying the most preferable divisions of interest to specialize in, should you decide later to enroll in graduate school.
17. Try to forecast the labor market needs and expectations. Be equally aware of opportunities and threats.
18. Revise and validate your original academic and/or career plan and design by seeking the advice of vocational counselors and/or experts in the field, or even by cross-referencing it with published information.
19. Join one or more bioengineering/biomedical engineering society or organization. This will offer immeasurable opportunities to keep track of advancements and breakthroughs in the said fields. In addition, it would provide an opportunity for national, regional, and global exposure.
20. Have a strong and well organized resume or curriculum vitae at hand. A good source would be that used by the European Commission on the following websites‡:

    - www.cedefop.eu.int/transparency
    - www.europa.eu.int/comm/education/index_en.html

    Another recommended source for preparing a resume or curriculum vitae is found online under the title '*Research and Training Opportunities at the National Institutes of Health—US Department of Health and Human Services*'‡:

    - http://www.training.nih.gov/careers/careercenter/cv.html

21. Work towards obtaining a license as a professional engineer (PE or PEng) soon after your graduation, because several years of experience are often mandatory before receiving this license. There are four main reasons for becoming a licensed PE or PEng: (1) it is a legal necessity in many countries; (2) it improves employment security; (3) it offers better opportunities for career advancement; and (4) it provides personal satisfaction [54]. It is worth noting that the requirements to accomplish such a process differ from one country or region to another. Should your country or region not provide professional licensure in Bioengineering/Biomedical Engineering, seek a license in a more generic engineering area, such as Electrical Engineering, Mechanical Engineering, or even General Engineering.
22. Be always prepared for a job interview.
23. Take part in life-long learning [25, 33, 35].
24. Perform a self check periodically that you are going in the right direction in the pursuit of your career path.

ACADEMIC CURRICULA

State of affairs: past, present, and future

Advancement in bioengineering/biomedical engineering curricula is an ever evolving process. To demonstrate, Katona used a 'bridge model' between *engineering* and *life sciences* to characterize the 'changing philosophies of biomedical engineering education' over three epochs: (1) *ca.* 1960–1980, the bridge was unidirectional and in general slender and weak—'engineering techniques were being applied to solve problems in the life sciences and medicine'; (2) *ca.* 1980–late 1990s, 'the biological revolution mandated that students' knowledge of the life sciences be broadened', as well as reinforcing the bridge and changing it into a two-way traffic; and (3) late 1990s–20??, bioengineering/biomedical engineering education supports an integrative approach with sufficient 'breadth and depth' that precludes the necessity for a bridge [10].

Today, programs in Bioengineering/Biomedical Engineering are divided into (1) those that offer a comprehensive curriculum in Bioengineering/Biomedical Engineering with emphasis on the biomedical sciences, and (2) those that specialize in a specific track option pertaining to the abovementioned divisions, to the exclusion of the bulk sum of the remaining divisions. It is worth noting that, even though a track curriculum usually yields expertise in a unilateral field or branch of Bioengineering/Biomedical Engineering, a fact that is very attractive to industry, it is debatable that such a track could become an impediment to flexibility and mastering the basics of the field, especially when the leading edge of Bioengineering/Biomedical Engineering is ever changing. Harmon recommended that 'Intermediate and high-level educational tracks must be made extremely flexible in order to accommodate the many multi-discipline sub-specialties' within this field [9]. This reality should be taken as a vital stepping stone in the design of new curricula in Bioengineering/Biomedical Engineering to be introduced throughout the world, particularly in developing and transitional countries.

Recommendations

Academic curricula in Bioengineering/Biomedical Engineering should well-equip prospective graduates with adequate expertise, both theoretical and applied, to confront the very increasing competitive reality that faces the young generations after they graduate. The main objective of these curricula should be in establishing a common knowledge base that should be required of prospective bioengineers/biomedical engineers, regardless of what division of the field they may go into. Before delving into the details of this section, the reader is strongly advised to consult the paper entitled '*Roles for Learning Sciences and Learning Technologies in Biomedical Engineering Education: A Review of Recent Advances*' [2]. Of particular interest in this paper, is the four barriers to be overcome when addressing curriculum issues in bioengineering/biomedical engineering education: (1) 'The Biology–Engineering Barrier'; (2) 'The Learning Science–Engineering Education Barrier'; (3) 'Technology–Education Barrier'; and (4) 'The Academe–Industry/Practice Barrier' [2].

For institutions of higher education that are willing to subscribe to the development of new undergraduate curricula in Bioengineering/Biomedical Engineering, particularly in the abovementioned countries where the ministries of higher education and other governmental agencies could also be involved, the following set of 10 recommendations needs to be considered:

1. To thoroughly adhere to the VaNTH-ERC recommendations pertaining to the five broad categories described earlier in the Literature Review section [23, 24].
2. To follow the Whitaker and ABET Curriculum Philosophies set by the Whitaker Foundation 2005 Summit Meeting [25, 33].
3. To use outcome measures aimed at assessing the success of the established curriculum in order to provide guidance to the curriculum planner [2, 21].
4. To collaborate with leading academic programs in Bioengineering/Biomedical Engineering worldwide, particularly within the European Community and the United States.
5. To integrate biomedical sciences courses into the bioengineering/biomedical engineering curricula [10].
6. To introduce a practical bioengineering/biomedical engineering training, cooperative education, or industrial internship program into the curriculum as a partial requirement towards the fulfillment of the undergraduate degree [15, 20, 30, 31].
7. To select specialized/qualified faculty with expertise and extensive knowledge in more than one division (multidisciplinary) of Bioengineering/Biomedical Engineering [23].
8. To launch the Bioengineering/Biomedical Engineering program at both levels of education: *theoretical* and *applied*; taking into consideration that learning technology, linked with new ideas from learning science, can result in increased effectiveness in student's learning [2].
9. To prepare competitive course syllabi that comply with the VaNTH-ERC and ABET standards. As well as to carefully and appropriately select course textbooks and references [23–25, 33].
10. To integrate simulation and modeling tools, multi-media teaching aids, and teaching resources into the various course syllabi within the Bioengineering/Biomedical Engineering program. Moreover, Harris *et al.* recommended the intensive use of 'case-based, problem-based, and project-based learning' while teaching biomedical engineering [2].

It is worth noting that the author does not claim that these recommendations are novel; however, they stem from his personal experience in bioengineering/biomedical engineering education. These recommendations have been used very satisfactorily in the curriculum model presented below.

The AUST undergraduate curriculum model

Despite the identified efforts to advance bioengineering/biomedical engineering education, there are vast areas of the world where it is still absent. A previous paper by the author described the dramatic deficiency in the role of bioengineering/biomedical engineering education within the Middle East and Northern African (MEDA) region; although the regional scene has been found to possess the potential of furnishing the Bioengineering/Biomedical Engineering field with the necessary auspicious socio-economic conditions [5, 55]. Nevertheless, the job opportunities in Bioengineering/Biomedical Engineering within this region are abundant and wait to be filled with the appropriate bioengineering/biomedical engineering expertise.

In an effort to remedy the above mentioned deficiency, and to respond to the local and regional socio-economic requirements, the American University of Science & Technology (AUST, Beirut, Lebanon) has developed a world-class competitive and comprehensive undergraduate program in Biomedical Engineering [5]. This program was founded in the spring term of 2002 and was carefully planned and thereafter customized in accordance with the VaNTH-ERC recommendations and the Whitaker and ABET Curriculum Philosophies [5, 55].

The undergraduate biomedical engineering curriculum at AUST is a post-freshman four-year program, leading to a Bachelor of Science degree in Computer and Communications Engineering (CCE) with minors in Biomedical Engineering (BME) and Biomedical Sciences (BMS). It is worth noting that the current status of degree-awarding in this major is still subject to government imposed constraints, pending final program accreditation on the part of the Lebanese Ministry of Higher Education. Nevertheless, while this goal is still a matter of earnest aspiration for AUST, the program is by no means undermined by such a contingency. The biomedical engineering curriculum, which is currently adopted at AUST, is shown in Table 3.

Nineteen students made up the first generation of biomedical engineers to graduate from this program between 2006 and 2007. Many of these students have been accepted for graduate studies in the said field at renowned academic institutions worldwide, such as Cornell University (Ithaca, New York, USA), New Jersey Institute of Technology (NJIT, Newark, New Jersey, USA), Politecnico University di Milano (POLIMI, Milan, Italy), Swiss Federal Institute of Technology—Zurich (ETH, Zurich, Switzerland), l'École Polytechnique Montréal (Montréal, Québec, Canada), l'Université de Technologie Compiègne (UTC, Compiègne cedex, France), and the Fach Hochschule Lübeck—University of Applied Sciences (Lübeck, Germany). The rest of the graduates have been employed in bioengineering/ biomedical engineering firms in Lebanon and abroad.

Based on its success, this curriculum may be recommended as a model for prospective undergraduate programs in Bioengineering/Biomedical Engineering, particularly within developing and transitional countries.

DISCUSSION AND CONCLUSIONS

The U.S. Department of Labor (DOL, Washington, DC, USA) has reported that 'the number of biomedical engineering jobs will increase by 31.4 percent through 2010 . . . double the rate for all other jobs combined.' Hence, the overall job growth in this field will by then average 15.2 percent [38]. Despite the overwhelming anticipated growth, employment indicators show that it is unlikely that this field will become saturated any time soon. This forecast for bioengineering/biomedical engineering jobs is reflected in Fig. 3, which highlights the student enrollment in Biomedical Engineering within the United States between 1975 and 2003. A particular feature of this figure is the rapid surge in bioengineering/biomedical engineering enrollment that begun in 1999.

Bioengineers/biomedical engineers are employed in universities, industry, hospitals, research facilities of educational and medical institutions, and in government regulatory agencies. Although most bioengineering/biomedical engineering graduates end up working in these environments, others use their emergent education as a springboard for building careers in fields such as medicine, law, and healthcare management. Viik and Malmivuo provided a useful extensive list of 'assignments and responsibility areas' in bioengineering/biomedical engineering jobs [21]: 'i) product development and design; (2) project assignments; (3) research; (4) sales and marketing; (5) data processing; (6) teaching and training; (7) technical and general design; (8) general/business management; (9) international trade assignments; (10) consulting; (11) quality-related assignments; (12) operation and maintenance; (13) personnel administration; (14) financial administration; (15) purchasing and materials assignments; (16) patenting assignments; and (17) production planning and management.'

Yet, a key question remains to be addressed: How much of an education would a bioengineer/ biomedical engineer require? Certainly, there is no dogmatic answer! In general, career advancement is contingent to the degree attained. A Bachelor's degree will enable the bioengineer/biomedical engineer to assume an entry level engineering position in a medical device or pharmaceutical company, a clinical engineering position in a hospital, or even a marketing position for a biomaterials or biotechnology company. Still, there are those who use this degree as a means to enroll in medical or dental school, while a few choose to join law school with the objective of working with patent law and intellectual property related to biomedical inventions. On the other hand, some bioengineers/ biomedical engineers choose to enhance their education by pursuing a graduate degree in business with the prospective goal of running a business or managing a healthcare organization. A Master's or Doctoral degree in Bioengineering/ Biomedical Engineering will open greater pathways in research and development, whether such occupation is in an industrial, academic, or government setting [53].

Given the above criteria, students have to work with great passion and diligence to realize a goal that they genuinely believe in. Once ready, these remarkable students will be capable of moving forward wherever opportunities allow them to thrive, further into the realms of Bioengineering/ Biomedical Engineering, and they will contribute to the advancement of knowledge in this vital humane field.

Despite the optimistic outlook conveyed earlier pertaining to the readiness of developing and transitional countries to engage in bioengineering/biomedical engineering education, it is feared that the acceptance of bioengineers/biomedical engineers within these regions may face the same difficult challenges as those encountered during the early days in the United States [9]. Thus, a word of advice to academic institutions of higher education, ministries of higher education, and other governmental agencies, who intend to launch or reform bioengineering/biomedical engineering curricula, is to be aware of these impediments and not to attempt to 'reinvent the wheel'. Valuable lessons could be learned from past experience as demonstrated in the Literature Review section of this paper. Harmon asserted that it is possible to overcome any existing obstacle that challenges the acceptance of biomedical engineers [9]. After all, 'the intent is not to build walls, which would be contrary to the very nature of the field, but to provide the necessary resources for educating students' as declared by Katona [10].

The current work of the author of this paper involves a study on the world proliferation of bioengineering/biomedical engineering education entitled 'Alexander the Great'. This project was launched in September 2007 by the Department of Biomedical Engineering at AUST; and aims at identifying, disseminating, and networking those institutions of higher learning that provide bioengineering/biomedical engineering education. The initial phase of this project, currently in progress, is to survey all 10 468 universities recognized by UNESCO (Paris, France), spread among the 193 member states of the United Nations (New York, NY, USA) within the six continents. The signifi-

Table 3. The undergraduate biomedical engineering curriculum at the American University of Science and Technology (AUST, Beirut, Lebanon)

BS in Computer and Communications Engineering
Minors in Biomedical Engineering & Biomedical Sciences
TOTAL REQUIRED CREDITS FOR GRADUATION
(Major CCE + Minor BME 120 Cr. Optional Minor BMS: 18 Cr.)

GENERAL GRADUATION REQUIREMENTS
(15 Credit Hours)

CSI	201	Introduction to Computing	3 cr.
ENG	201	Composition & Rhetoric I	3 cr.
ENG	202	Composition & Rhetoric II	3 cr.
ENG	205	English Communication Skills	3 cr.
HMS	220	Arabic Communication Skills	3 cr.

FREE LIBERAL ARTS & NATURAL SCIENCES ELECTIVES
(9 Credit Hours)

HMS	250	Methodology of Research	3 cr.
SOS	230	Introduction to Psychology	3 cr.
SOS	231	Social Psychology	3 cr.
SOS	235	Introduction to International Relations	3 cr.
SOS	240	Introduction to Sociology	3 cr.
CHE	201	General Chemistry (*Required for minor in BMS*)	3 cr.
CHE	210	Organic Chemistry (*Required for minor in BMS*)	3 cr.

MATHEMATICS REQUIREMENTS
(15 Credit Hours)

MAT	203	Calculus III	3 cr.
MAT	205	Linear Algebra	3 cr.
MAT	210	Probability & Statistics for Science	3 cr.
MAT	225	Differential Equations	3 cr.
MAT	315	Numerical Methods	3 cr.

COMPUTER AND COMMUNICATIONS ENGINEERING
MAJOR REQUIREMENTS
(46 Credit Hours)

CCE	201	Circuit Analysis I	3 cr.
CCE	201L	Circuit Analysis I Laboratory	1 cr.
CCE	202	Circuit Analysis II	3 cr.
CCE	202L	Circuit Analysis II Laboratory	1 cr.
CCE	220	Digital Systems	3 cr.
CCE	220L	Digital Systems Laboratory	1 cr.
CCE	301	Electronics	3 cr.
CCE	301L	Electronics Laboratory	1 cr.
CCE	320	Computer Organization & Microprocessors	3 cr.
CCE	320L	Computer Organization & Microprocessors Laboratory	1 cr.
CCE	325	Computer Architecture	3 cr.
CCE	401	Communication Systems	3 cr.
CCE	401L	Communication Systems Laboratory	1 cr.
CCE	406	Digital Signal Processing	3 cr.
CSI	205	Computer Programming I (Functional Programming)	3 cr.
CSI	205L	Computer Programming I Laboratory	1 cr.
CSI	250	Computer Programming II (Object-Oriented Programming)	3 cr.
CSI	250L	Computer Programming II Laboratory	1 cr.
CSI	311	Java Programming	3 cr.
CSI	311L	Java Programming Laboratory	1 cr.
CSI	345	Computer Networks	3 cr.
CSI	345L	Computer Networks Laboratory	1 cr.

BIOMEDICAL ENGINEERING MINOR REQUIREMENTS
(29 Credit Hours)

BME	200	Introduction to Biomedical Engineering	3 cr.
BME	210	Introduction to Biomechanics I: Solid Mechanics	3 cr.
BME	212	Introduction to Biomechanics II: Dynamics	3 cr.
BME	317	Electrical Biophysics	3 cr.
BME	330	Signals and Biosystems	3 cr.
BME	400	Practical Biomedical Engineering Training	1 cr.
BME	405	Biocontrol Systems	3 cr.
BME	405L	Biocontrol Systems Laboratory	1 cr.
BME	481	Biomedical Instrumentation & Design	3 cr.
BME	481L	Biomedical Instrumentation & Design Laboratory	1 cr.
BME	490	Biomedical Engineering Ethics	1 cr.
BME	497	Biomedical Engineering Project Proposal	1 cr.
BME	499	Biomedical Engineering Senior Project	3 cr.

BIOMEDICAL ENGINEERING TECHNICAL ELECTIVES
(6 Credit Hours)

BME	301B	The Human Body: Structure & Functions	3 cr.
BME	310B	Biomedical Materials Considerations	3 cr.
BME	450B	Biomedical Engineering Design	3 cr.
BME	476B	Biofluid Mechanics	3 cr.
BME	483B	Introduction to Magnetic Resonance Imaging	3 cr.
BME	485B	Introduction to Optical Imaging	3 cr.
BME	487B	Biomedical Robotics	3 cr.
BME	489B	Artificial Intelligence in Medicine	3 cr.

ADDITIONAL REQUIREMENTS FOR MINOR
IN BIOMEDICAL SCIENCES
(18 Credit Hours—*Optional*)

BCH	210	Biochemistry	3 cr.
BIO	210	Cells & Molecules	3 cr.
BIO	210L	Cells & Molecules Laboratory	1 cr.
BIO	231	Biology of Organisms	3 cr.
PSL	210	Introduction to Physiology	3 cr.
PSL	210L	Physiology Laboratory	1 cr.
PSL	319	Quantitative Physiology	3 cr.
PSL	319L	Quantitative Physiology Laboratory	1 cr.

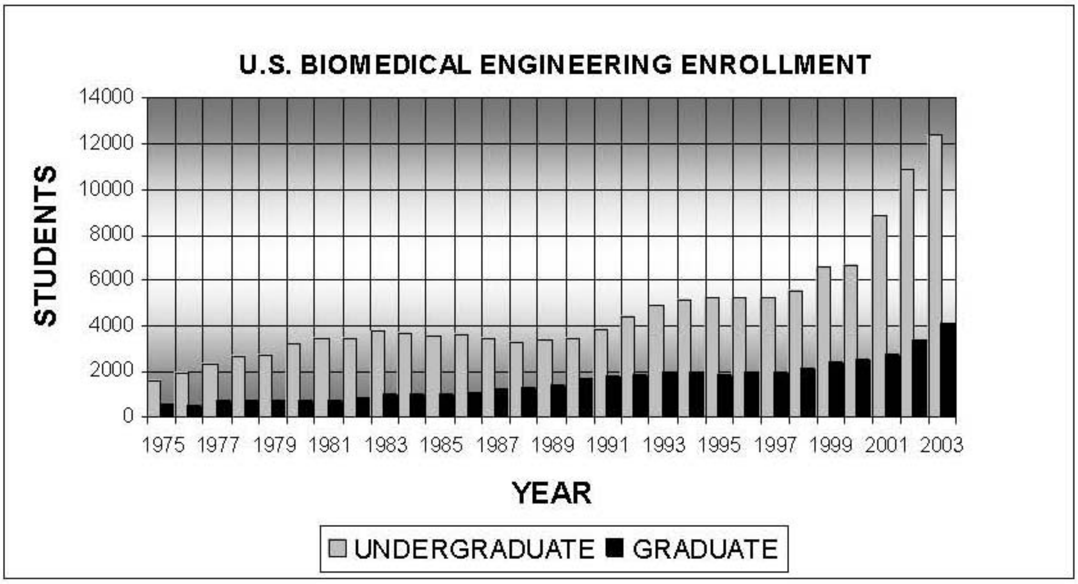


Fig. 3. Undergraduate and graduate student enrollment in Biomedical Engineering in the United States between 1975 and 2003. (Data was reproduced by digitization from the Whitaker Foundation website [25], and extended from Pilkington *et al.* [4].)

cance of this project is: (1) the global networking of bioengineering/biomedical engineering academic and research programs; (2) the diffusion of first-class bioengineering/biomedical engineering education and the global promotion of this field; (3) the establishment of framework agreements for cooperation in Bioengineering/Biomedical Engineering among the identified academic institutions offering curricula in this field; and (4) the erection of bridges among educational institutions, industry, and professional societies involved in Bioengineering/Biomedical Engineering. It is estimated that this project would be ready in 2009 and its progress delineated in the literature.

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‡ All Uniform Resource Locators (URL) in this paper were accessed on March 10, 2008.

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