Biomedical Engineering Redux: Emerging Career Opportunities and Their Implications for Educational Programs

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I. Background.

Biomedical engineering combines engineering expertise with the needs of the medical community for the enhancement of health care. [1] [2] Working cooperatively with scientists, chemists, and medical professionals, biomedical engineers design and develop devices associated with the biological systems of humans and animals. Their work spans a host of applications: computers used to analyze blood; laser systems used in corrective eye surgery; artificial organs; imaging systems (e.g., ultrasound); automating insulin injections or controlling body functions – to name a few. In addition to sound preparation in one of the basic engineering programs such as electrical, chemical or mechanical engineering, specialized training may be required in such areas as biomaterials, biomechanics, medical imaging, rehabilitation, or orthopedic engineering. (Such extensive educational requirements places a severe strain on traditional four-year engineering programs.) A 'mission statement' for Biomedical engineering can be extracted from these relevant applications and extended to include basic life sciences:

> The discipline of biomedical engineering seeks to advance knowledge in engineering, biology, and medicine to improve human health through inter-disciplinary activities including: the acquisition of new knowledge and understanding of living systems; the development of new devices, algorithms, and systems that advance biology and medicine and improve medical practice and health care delivery.

From the perspective of an electrical engineer, biomedical engineering as a discernible specialization can trace its origins to the early part of the 20th century. [3] Physical scientists such as Herbert Gasser and Detlev Bronk enlisted the expertise of electrical engineers to develop instruments (e.g., a rudimentary cathode ray oscilloscope) that permitted them to work out the structure and functions of individual nerve fibers in the sciatic nerve of the frog, or to disclose the structure and function of the olfactory nerve. (Alan Hodgkin and Andrew Huxley used the voltage clamp technique to measure changes in permeability of the nerve cell membrane to sodium, potassium and chloride ions during a nerve impulse leading to the formulation of a mathematical model for the cellular dynamics of the nerve impulse.) Many of these individuals went on to win Nobel Prizes.

Major advances in medical instrumentation occurred during World War II (as well as in subsequent wars) and as a consequence, a number of colleges and universities developed programs designated as Biomedical engineering (or simply Bioengineering) in response to, and in expectation of, increased demand from industry in support of the medical community. However, outside of some niche positions (e.g., clinical engineer) or research arrangements, the 'supply' exceeded the 'demand.' Consider a snapshot of biomedical engineering employment as of 2000.[(1)]:

- Biomedical engineers held about 7200 jobs.
- Manufacturing industries employed 30 percent of all biomedical engineers, primarily in the medical instruments and supplies industries.
- Others worked for health services; some also worked on a contract basis for government agencies or as independent consultants.

Compare this to an estimate of how many professionals may have been produced by undergraduate biomedical programs from 1979 through 1999. [(4)] From 1979 through 1999, a total of some 90,000 (aggregate) students were enrolled in (undergraduate) bioengineering programs. Assuming that these students required 4 years to complete their training, the potential number of bioengineering professionals produced during this time approaches some 22,500. Before accounting for demographic changes in the professional population (e.g., bioengineers moving on to other specializations), the ratio of supply to demand reflects an imbalance between current employment needs and the aggregate available supply.

Many of the programs introduced during this period exhibited a 'characteristic' curriculum built on a basic course sequence in electrical engineering supplemented by several courses related to Biology and Physiology; these courses typically replaced elective alternatives available to students within the electrical engineering major. In recognition of these programs, the Accreditation Board for Engineering and Technology (ABET) accordingly developed Program Criteria[(5)] with its principal provision as follows:

"The program must demonstrate that graduates have: 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; 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."

Enrollment trends over the 1979 – 1999 period are summarized in Figure 1 (below) extrapolated from data taken from the Whitaker Foundation web site.([4]). In Figure 1, the trend line represents a moving average of the percentage of engineering students who are enrolled as bioengineering majors. From 1979 through 1990, enrollment remained relatively constant (as a percentage); during the last decade, the percentages of bioengineering majors has virtually doubled. (Absolute enrollment in bioengineering has increased dramatically over the last decade while total engineering enrollments have remained relatively flat (or even decreased) over the similar period.) The reason for this increased interest derives from the monumental changes taking place in the delivery of health care in the United States (as well as the world as a whole).

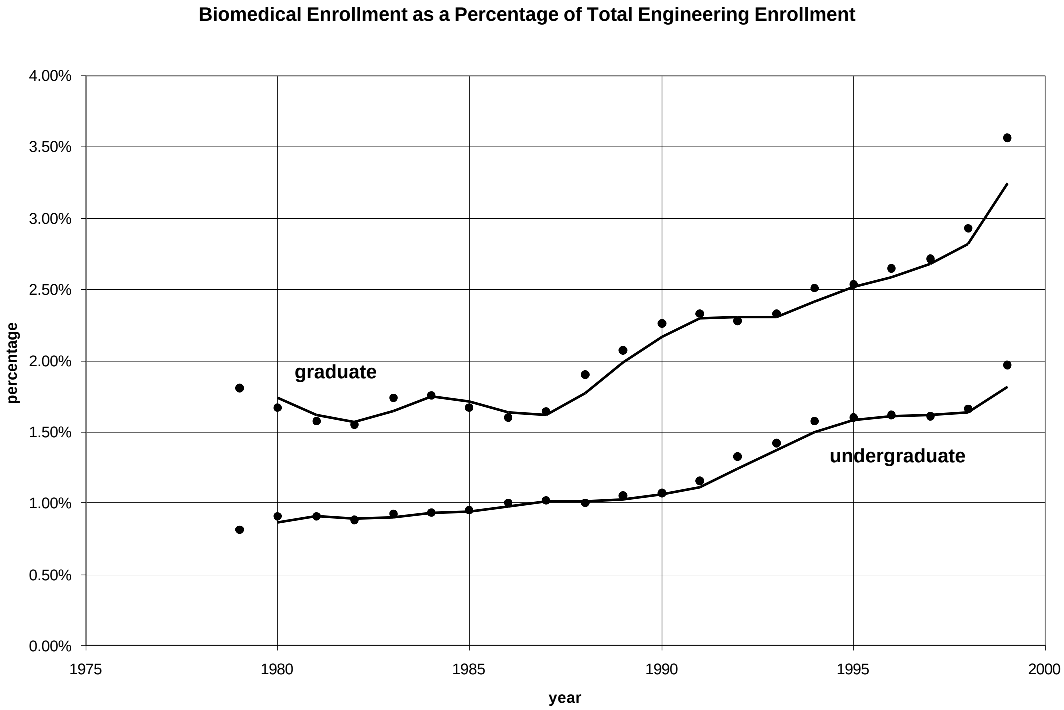

Figure 1. Undergraduate and graduate enrollment trends in bioengineering, 1979 –1999.

II. New Bioengineering Technologies.

The scope of emerging technologies in bioengineering range from "nanotechnology" to highly abstract applications involving artificial intelligence (AI). Two examples serve to demonstrate the extremes.

Telemedicine/Telerehabilitation

Physical therapeutic techniques have recently been augmented by the use of personal computers (PC), which greatly enhances delivery of such services including improvement of evidence-based outcomes at reduced cost. [(6)]. AI, in combination with modern PCs and communications networks have the potential to overcome the problems associated with modern clinical rehabilitation (e.g., high cost, ineffectiveness, and inefficiency) and to extend delivery of rehabilitation health services to those ordinarily not able to benefit from therapy. [(7,8)] A system for enabling this is depicted in Figure 2. A Physical Therapist ("Supervisor") remains in concurrent contact with several patients, supervising their rehabilitation in real time. An array of sensors collects information from each patient and relays it to the therapist using the communication capabilities of either a Local Area Network or Internet; the therapist is normally located in a remotely situated health care facility. The infrastructure provides for display of attempted as well as desired patient movement patterns. It can provide real time feedback for shaping a patient's motor control of a dysfunctional limb – such as that resulting from stroke – using AI.

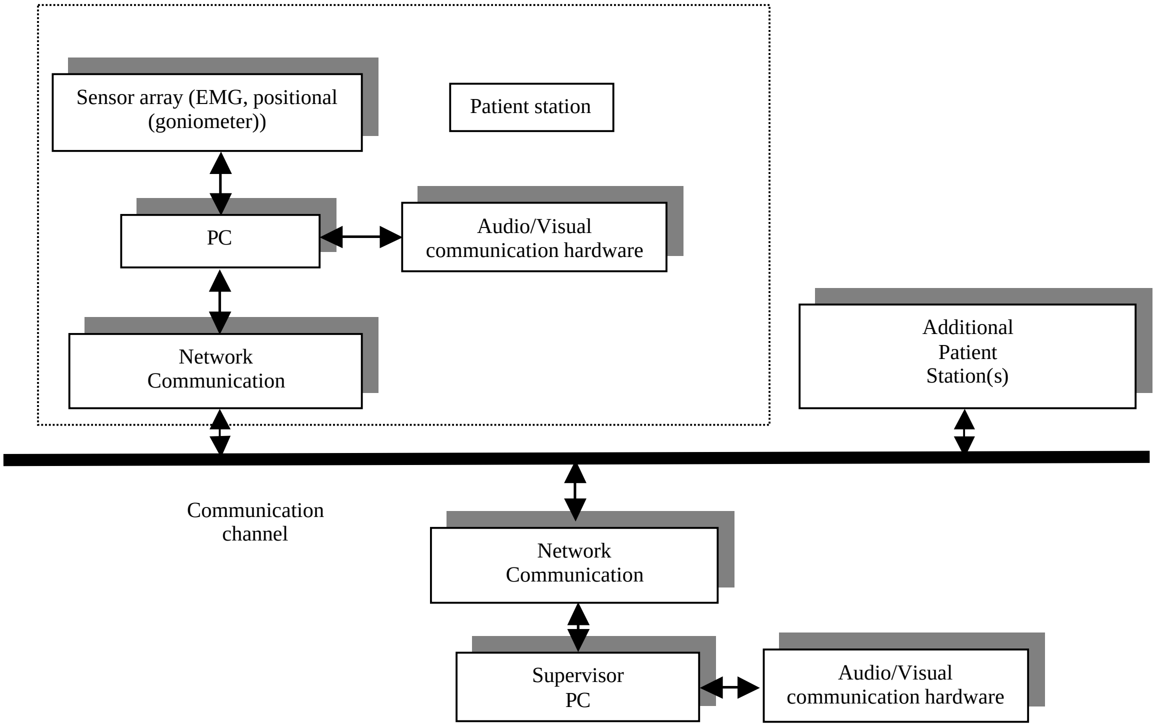

Figure 2
Block Diagram of Multi-patient Rehabilitation System

Nanotechnology.
Cellular drug delivery, the genomics revolution, spinal cord repair, organ growth are among the recent medical breakthroughs that bioengineers have helped to generate within the field of expertise generally referred to as nanotechnology. [9]

Numerous life activities and protein surface interactions take place in cell environments where dimensions are measured in nanometers. Engineers are exploring the possibilities of extremely small machines and tools that can enter the human body. By using a person's saliva, body fluids or blood, nanobiosensors can be created to reliably detect pathogens such as viruses. It is possible that nanotechnology will provide the ability to monitor and measure a virus like AIDS, which averages 100 nanometers.

Within tissue engineering, a scaffold measuring only 50 nanometers in diameter can be built using nanofibers. By controlling the surface properties of these fibers, artificial tissues can be grown on them for various applications such as burn treatment. This might eventually lead to the ability to interact with cells to form functional tissues for a liver or kidney.

In drug delivery, bioengineers are exploring molecules that can be encapsulated within a shell (such as a liposome vesicle) with properties that allow drugs to be released in a controlled fashion. Bioengineers are researching ways to functionalize these shells for site-specific targeting and sensing applications. Drug development costs can be reduced using nanochips to test various medications or combinations of chemicals. Using extremely thin and sharp nanoprobes, bioengineers hope to be able to enter a cell, leave a few molecules of a particular drug behind and then exit the cell (leaving the cell intact and alive).

In recognition of the importance of this emerging field, the Institute of Electrical and Electronic Engineers (IEEE) plans to offer a new journal – IEEE Transactions on Nanotechnology – in 2002.

Other examples of the rapidly changing needs of the medical community abound.[10, 11] Digital processing of EEG (as well as other neurological) data is a challenge that will test the ability of multiple disciplines to come together to break through professional barriers. It provides a hope in the quest to understand these signals from the basic origin to their potential to be used in therapy.

III. Educational Challenges and Responses.

It is a clear premise of this discussion that, from an educational point of view, bioengineering is: inter- and multi-disciplinary in nature. It will place a burden of continuing education – either formal (graduate study) or informal (e.g., research, conferences) on its practitioners. The current undergraduate fashion based on traditional (historical) approaches should be revised. How best, then, can the educational community serve the needs of these professionals? Two alternatives surface: (1) develop specialized programs; (2) provide broad programs that address the underlying educational skills required of bioengineers. Examples of both are possible, with complementary advantages and disadvantages.

Specialized Programs.
Recognizing that student interest, industrial growth, and medical advances have highlighted a growing need for baccalaureate trained engineers, the University of Illinois at Chicago (UIC) has developed a new program with technical emphasis in molecular biology, nanotechnology, and computational modeling. [12] It is based on the view that the future bioengineer can be expected to design, model, fabricate and control living systems and their fundamental constituents at the same level of detail as an electrical engineer uses SPICE and CAD tools to develop a microelectronic or micro-electro-mechanical device.

Rapid industrial growth in Biotechnology and genetic engineering have spawned new engineering curricula in cell and tissue engineering, bioinformatics, and neural engineering curricula; this has not yet fostered the full development of bioengineering and degree programs particularly at the baccalaureate level.

To guide the approach, UIC used the following list assumptions as a guide to this effort:

(1) Four Year Curriculum;
(2) Preparation for Industry and for Graduate School,
(3) Rigor in Math/Physics/Chemistry/Biology,
(4) Focus on Biology-based Engineering,
(5) New Focus Areas Identified, and
(6) Required Core Course Sequences.

The curriculum developed at UIC is designed to provide the baccalaureate graduate with the tools needed to succeed at an entry level engineering position in the emerging bioengineering and biotechnology industries.

The curriculum has been designed in cooperation with a departmental industrial advisory committee representing companies such as Abbott Laboratories and Baxter International. The suggestions of the advisory committee, along with faculty leadership and institutional support, led to the establishment, in the department of bioengineering, of three new curricular focus areas in:

1. cell and tissue engineering;
2. neural engineering; and
3. bioinformatics

The core bioengineering courses should better prepare its graduates to model, design, fabricate, test, and control not just sensors and systems, but increasingly genomes, proteins, and living cells as well as the interface with external systems.

Bioengineers need to become as comfortable transforming the genome of a cell as they are at identifying the transfer function of a system model. UIC believes that the future technologies are to be, largely molecular, chemically driven, and biology-based and hence, the emphasis in the curriculum on molecular biology, nanotechnology, and computational modeling.

UIC does not propose that all programs accept the proposed model. They assume that this approach can be used to strengthen bioengineering curriculum in which the paradigm (identify a theme, develop a core, and establish course sequences) can be used as a framework for constructing other similarly focused and independent bioengineering programs.

Key components to the curriculum include:

1. an early and rigorous introduction of cell biology and organic chemistry, in addition to fundamental engineering principles;
2. bioengineering courses that focus on the molecular, cellular, and tissue levels of complexity;
3. laboratory based courses that focus on emerging interfacial technologies in characterization and fabrication;
4. opportunities for practical real-world experience through senior design, summer internships, or semester long coop jobs.

Similar efforts are underway at UIC in the areas of bioinformatics and neural engineering. Engineering technical electives in subjects such as circuit design and analysis, materials science, thermodynamics, and computer science are common to all UIC engineering programs. Few elective hours are available for juniors and seniors, focused course sequences are the norm, and little, if any, flexibility is granted in core course selection..

Generalized Programs

In general, employers of our engineering students are less likely to house their engineers in separate 'holes.' [13] They are hardly lumped together in terms of their academic preparations.

Each time the objectives get changed, the 'team' is regrouped so as to successfully attack the newest problem. However, as the modern university took shape, disciplinarity was reinforced in two major ways: industries demanded and received specialists; disciplines recruited students to their ranks.[14] The two paradigms are in irreconcilable conflict. ABET has already taken sides in requiring programs to prepare their graduates with skills to function on multidisciplinary teams, and a broad education to understand the impact of engineering solutions in societal and global contexts (Engineering Criteria 2000). How, then, to meet the needs of ABET, institutional missions, the Bioengineering community (industry, research), and student interests?

For many institutions, the commitments necessary to support specialized programs such as the one noted above are not possible. For such colleges and universities, a broad-based program within existing baccalaureate structures is possible. Academia, in spite of its focus on clear-cut disciplines claims that it is able to prepare its students for a world that is a lot more flexible and adaptable. Our former students end up becoming students many times over throughout their lives digesting all kinds of materials which is clearly beyond the scope of their original major. Newer fields end up sliding back to the mold of newer departments – academia's favorite safety net. Traditional disciplines fight each new venture. The newer Department gets ready to wage a war against all yet-to-occur newer efforts that might threaten to take away its resources. [13]

Characteristics of a generalized engineering curriculum that will meet the dynamic needs of the Biomedical community, ABET, institutional missions, and student interests may be characterized as having:

1) broad based basic preparation in science, mathematics and discipline-specific engineering science;
2) a sequence of upper division elective courses that explore selected topics (themes) in a complete and rigorous manner.

For example, a representative *electrical* engineering program that would prepare students for entry level opportunities in Bioengineering could be designed with the components shown in Table 1 (below). The program is certainly not unique but includes an acceptable number of credits, and is reasonably flexible allowing institutions to meet their own missions, goals, and objectives.

Data Acquisition and Analysis is an important element of the program and would provide basic information for transducers and computer-based (icon-driven) acquisition of biomedical-related signals (with enough generality to permit this course to be used in a 'pure' electrical engineering program). Key to this sample program is the inclusion of (12) "Elective concentration" credits. Suitable sequences of courses could support preparation (depth) in two areas of study that would prepare graduates for entry level opportunities in the emerging Biomedical technologies. Examples of such sequences are shown in Table 2 (below).

Table 1
Topical Composition of Engineering Program Suitable for Bioengineering Training

Component	Credits
English, Humanities and Ethics	30
Basic science (with labs) and mathematics	24
Network Analysis, signal processing and related courses (e.g., control systems, communications)	27
Electronics (including digital systems, and microcomputers)	12
Advanced Engineering Mathematics and Electromagnetic Theory.	6
Data Acquisition and Analysis (including statistics)	6
Engineering laboratories and capstone design	10
Discipline-related (e.g., Thermodynamics or other course suitable for Bioengineering preparation)	3
Elective concentrations	12

This produces a program comprising 130 credits. (Elements of design, computer literacy (including high level language programming), and interdisciplinary concepts are considered to be distributed throughout the coursework.)

Table 2
Sample Elective Concentration Sequences

Biomedical Area	Course 1	Course 2
Image Processing	Optronics	Image Processing
Biomedical Data Processing	Operating Systems	Databases
Telemedicine	Telecommunications (including computer networks)	Multimedia

(These courses would include some application examples that are suitable for bioengineering. For efficiency some courses might support more than one specialization (e.g., Multimedia could be used for a specialization in Biomedical Automation (as well as Artificial Intelligence).).

IV. Summary.
Traditional programs in Biomedical Engineering are often unresponsive to the rapidly emerging needs of the Biomedical community, particularly at the undergraduate level. Two paradigms (as well as their various combinations) provide ‘bookends’ for potential models: targeted (specialized); generalized. The advantages and disadvantages of these are summarized in Table 3.

Table 3
Summary of Characteristics of Specialized and Generalized Bioengineering Programs

Characteristic	**Specific**	**Generalized**
Cost	Costly, if new department is needed.	Minimal cost; can be integrated into existing programs
Preparation	Highly focused; excellent preparation.	Diffuse; will surely require postgraduate or professional education.
Flexibility	Less flexible, particularly as new specializations develop.	Highly flexible but at the expense of more limited preparation.
Disciplinarity	Inter-disciplinary; usually with professionals in a single specialization area.	Multi-disciplinary; preparation to communicate with professionals with varying specializations.

References:
(1) U.S. Department of Labor, Occupational Outlook Handbook. (http://stats.bls.gov)
(2) The Whitaker Foundation: Biomedical Engineering and Bioengineering at a Glance. Whitaker Foundation web site (www.whitaker.org) .
(3) Schoenfeld, R.L. From einthoven's galvanometer to single channel recording with electronics, neuroscientists get inside the membrane, Private communication. In press, IEEE Spectrum, 2002.
(4) The Whitaker Foundation: Student Enrollments in Biomedical Engineering and Bioengineering, BME @ A Glance; Whitaker Foundation web site.
(5) 2001-2002 Criteria for Accrediting Engineering Programs,
(6) Brudny, J., Biofeedback. In: *Rehabilitation Medicine*, ED.: Goodgold, J., C.V. Mosby Co., St. Louis, 1988.
(7) Silverman, G., Artificial intelligence in rehabilitation medicine: an emerging technology. In: *Proceedings of the IASTED International Conference on AI and Applications*, Marbella, Spain, 2001.
(8) Siverman, G., Dworkin, B.R., Instrumental behavior shaping automata. In *Digital Biosignal Processing*. Ed.: Weitkunat, R., Elsevier, 1991.
(9) Kowalenko, K. Nanotech: the new frontier in biomedicine, *The Institute*, 25, 8, August 2001.
(10) Colditz, P.B., Burke, C.J., Celka, P., Digital processing of EEG signals, IEEE Engineering in Medicine and Biology, September/October 2001.
(11) Want., P.K., Digital EEG in clinical practice. Philadelphia, PA., Lippincott Raven, 1996.
(12) Desai, T.A., Magin, R.L., A cure for bioengineering? A new undergraduate core curriculum, *Journal of Engineering Education*, April 2001.
(13) Karim, M.A., Engineering: diversity of disciplines and of students, *The Interface*, November 2001.
(14) Klein, J.T., *Interdisciplinary: history, theory and practice*, Wayne State University Press, Detroit, 1991.

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