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DNA of Biological Engineering: An Engineering Discipline?*

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A fundamental question is whether biological engineering will become a science-based engineering discipline (like mechanical engineering, electrical engineering, chemical engineering, civil engineering, etc.) or be a subject area where engineering is applied to biological systems. My conclusion, which is presented in this paper, is that biological engineering has the 'DNA' and rational structure to be a well grounded engineering discipline with a mature industry to support its graduates. Also, it is essential that biological engineers adopt a definition of biological engineering and use it consistently in all communications. To do otherwise will add to the confusion about biological engineering and continue to contribute to fragmentation.

Keywords: biological engineering discipline; industry expectations

INTRODUCTION

THE NEED to create an intellectual focus for biological engineering as a discipline and to define the body of knowledge for the discipline constitutes a fundamental issue. During the annual meeting of the Institute of Biological Engineering (IBE) at Sacramento in 2001, a Workshop, 'DNA of Biological Engineering: Defining the Body of Knowledge for the Discipline,' sought to engage academic and non-academics in search of the 'discipline'.

A fundamental question is whether biological engineering will become a science-based engineering discipline (like mechanical engineering, electrical engineering, chemical engineering, civil engineering, etc.) or an applied area where engineering is applied to biological systems. There is no clear answer to this question given different institutional cultures but my bias is that for the long-term future and development of biological engineering, we should pursue a path to begin the process to create biological engineering as an engineering discipline.

As we address the development of biological engineering several fundamental questions arise:

- What is biological engineering?
- What is the 'body of knowledge' that makes up the discipline?
- What are perceptions of the industrial sector?
- How do we communicate an understanding to the public of who we are and what we do as biological engineers?

OBJECTIVES

My objectives in this paper are:

- Create an intellectual focus for biological engineering as a biologically and science based engineering discipline;
- Provide a definition of biological engineering;
- Suggest the elements of a curriculum in biological engineering; and
- Offer perceptions of the industrial sector about biological engineering.

WHAT IS BIOLOGICAL ENGINEERING?

During my term as president of IBE in 2001 and as a follow up to the IBE 2001 meeting, we developed a definition with the input of the IBE membership:

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

The IBE membership and IBE Council spent considerable time and energy to develop a definition that could provide a common understanding of biological engineering. In my opinion this definition is well crafted in its focus on key elements. These key elements are:

- an engineering discipline;
- biology-based foundation;
- fundamental concepts of biological systems
- an appreciation for applications,
- scale from the molecular to large system.

The reality is that beyond a small number of IBE members this definition has not had widespread adoption and usage resulting in many various definitions, which while they all have rationality tend to leave a fragmented understanding. Also, some have chosen to emphasize particular areas, which creates uncertainties about a comprehensive understanding of the 'new' discipline.

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WHAT IS THE DNA OF BIOLOGICAL ENGINEERING?

A number of persons have offered their thoughts about a curriculum for biological engineering. Scott [9] addressed the promise of biological engineering and suggested a basic undergraduate curriculum for biological engineering that would meet ABET criteria. However, this curriculum, although steeped in a biologically-based philosophy was more consistent with the concept of the application of engineering to biology rather than a discipline-based biological engineering. More recently a number of persons and the Department of Biological and Environmental Engineering at Cornell University have evolved a perspective for a curriculum that focuses on a biology-based discipline of biological engineering.

Johnson and Phillips [5] presented a set of philosophical foundations of biological engineering. Penfield [7] in a presentation to the ABET Board of Directors, argued that there will be a discipline of biological engineering. Penfield suggested that biological engineering (BE), not biomedical engineering, would be based on molecular and cell biology; would impact all existing disciplines; BE is not here yet; we should be planning for it today; and the best way to define it would be to develop and teach an undergraduate curriculum. Lima *et al*. [6] present a model for integrating skills across the biological engineering curriculum, but this model is primarily focused on the application of engineering to biological systems with particular emphasis on communication skills.

Johnson and Phillips ([5] have thoroughly addressed issues of a conceptual framework for a curriculum, competencies, basic engineering and biological concepts, common courses, interfacing between engineers and biologists, and employment and I refer the reader to their excellent and comprehensive presentation. Building on many of these points, Gebremedhin [2] at the 2001 IBE Annual meeting offered an example curriculum for incorporating core concepts into a BS degree program in biological engineering.

Since this meeting, the Department of Biological and Environmental Engineering, at Cornell University, has developed a discipline-based curriculum of undergraduate study. We have sought to create a coordinated array of courses (semester hours in parentheses) to build a biology-based disciplinary curriculum for our students (see below).

Core sciences (46):
- Mathematics (16)
- Physics (8)
  - Mechanics and heat
  - Electricity, magnetism and optics
- Chemistry (7)
  - General chemistry
  - Organic chemistry
- Biological science (15)
  - Introductory biology with laboratories (8)
  - Biochemistry
  - Cellular biology or genetics or molecular biology

Core engineering courses (15):
- Computer programming
- Engineering distribution
  - Principles of biological engineering
  - Probability and statistics
  - Mechanics of solids

Core biological engineering courses (22):
- Bio-kinetics and thermodynamics
- Biotransport (heat and mass)
- Biofluids (not yet developed, so students are now taking 'regular' fluids)
- Biomaterials
- Bioinstrumentation
- Physiological engineering
- Molecular and cellular bioengineering

Biological engineering electives (13) (electives chosen from courses within the following concentrations or across these concentrations):
- Biomedical engineering
- Bioprocess engineering
- Bioenvironmental engineering
- Computational biological engineering

Liberal studies (24)

Approved electives (6)
This gives a total of 126-semester hours minimum.

The above curriculum contains 96 semester hours that might be called a biology-based biological engineering curriculum with a fair amount of prescription except for the 13 hours of biological engineering electives, the 24 hours of humanities and social sciences (liberal electives) and approved electives. (These are actually much more open than the word 'approved' might suggest.) The core biological engineering courses, which are offered by the Department of Biological and Environmental Engineering (BEE), deserve a bit of discussion because they, more than any other segment of the curriculum, represent a major redirection of BEE to create a biologically based discipline of biological engineering.

Principles of biological engineering (new course, taught once):

A first course introducing principles of biological engineering. Integration of biology with engineering, mathematics and physical principles.

Bio-kinetics and thermodynamics (new course, taught for three years):

Principles of kinetics and thermodynamics presented as energy flows and cycles in the context of biological and environmental systems.

Bio-fluids (new course under development):
Basic principles of fluid flow, including non-Newtonian flow in the context of biological systems.

Bio-transport (course taught for 12 years with revisions):
Fundamentals of energy and mass transport for biological and environmental systems.

Bioinstrumentation (course taught for 10 plus years):
Biological and biomedical instrumentation are emphasized in a laboratory-based course. Sensors and signal conditioning techniques used in biology and medicine are examined as well as image processing techniques.

Biomaterials (taught for 10 years):
The course includes elastic, viscous and viscoelastic properties; thermal and mass transport properties of biomaterials with a laboratory.

Physiological engineering (taught for 15 years):
The themes are signal processing related to neural conduction, acoustic signals, vision and image processing and analysis of cardiovascular and respiratory systems and bioenergetics of animals and humans. Laboratories are included in the course.

Molecular and cellular bioengineering (new course which has been offered twice):
Biological engineering at the molecular and cellular level focuses on different organisms of viruses, bacteria and cells at the scales of nano, molecular, cellular, tissue and environment with two underlying themes of DNA and cancer.

The extended core of biological engineering courses above provides substantial structure and content to the Department's disciplinary and biologically based engineering program. We have developed the philosophy of four concentrations for biological engineering electives (13 hours):

- biomedical engineering
- bioprocess engineering
- bioenvironmental engineering.
- computational biological engineering.

These electives can be chosen from a very extensive set of courses within a specific area of concentration or across the concentrations. Thus, the students can pursue, according to their interests, specific courses within an area or with more generality courses in more than one area. To illustrate the character of these concentrations a list of some of the potential courses is provided for each area of concentration. Where the BEE department offers the course it is so designated by BEE. However, we do not limit the selection of courses to the BEE department and show, for purposes of illustration, the many available course options within the University and the interdisciplinary richness of the curriculum.

1. Biomedical Engineering
- Biophysical methods
- Biosensors (BEE)
- Computer aided engineering: applications to biomedical processes (BEE)
- Biomedical engineering of metabolic structures
- CDE in biomedical system design
- Bioelectric signal analysis & processing
- Computer analysis of biomedical images
- Orthopedic tissue mechanics
- Biomedical engineering
- Fundamentals of biomedical engineering I & II
- Biomechanical systems

2. Bioprocess Engineering
- Biosensors (BEE)
- Bioseparations (BEE)
- Ecological engineering (BEE)
- Metabolic engineering (BEE)
- Tissue culture engineering
- Intro to bioprocess engineering

3. Bioenvironmental Engineering
- Aquaculture (BEE)
- Environmental systems analysis (BEE)
- Solid waste engineering (BEE)
- Ecological engineering (BEE)
- Sustainable energy systems (BEE)
- Bioremediation: Engineering organisms to clean up the environment (BEE)
- Sustainable development seminar (BEE)
- Environmental quality engineering images
- Microbiology for environmental engr.

4. Computational Biological Engineering
- Computer aided engineering: applic. to biomedical processes (BEE)
- Biomechanics of plants (BEE)
- Biological engr. analysis (BEE)
- Numerical Methods in computational molecular biology
- Computational molecular biology
- Computer analysis of biomedical
- Mathematical ecology

It is very clear from the presentation of the curriculum above that BEE at Cornell has evolved dramatically from its roots in agricultural engineering. We are committed to a path of being among the pioneering departments, which define and develop the discipline of biological engineering.

WHAT PERCEPTIONS DOES INDUSTRY HAVE FOR BIOLOGICAL ENGINEERS?

This is a very difficult question to answer, partly because many in industry ask, what is biological engineering? At the 2001 IBE Annual meeting [1, 8] two persons from the biotechnology industry provided insights from their perspective of the biotech industry. Brockwell (Genentech) felt that a biologically based biological engineering program is a very appropriate degree program for graduates who would be employed in her division and similar divisions at Genentech. From a differing perspective, Schembri (Agilent Technologies), suggested that a bioengineering degree program should be one where the student completes a standard engineering degree program to gain significant depth in one area (EE, ME, Chem. E, etc.) and includes a 'minor' interest in biological engineering (general biology, physiology, biochemistry, organic chemistry and molecular biology).

I am not surprised by these different responses to the role of biological engineers in industry, and believe it represents both an uncertainty about what is a biological engineer and the fact that the biotechnology and life sciences industries have greatly varying needs for engineers. Johnson and Phillips [5] suggested that biological engineers should be readily employable (at least more so than biomedical engineers) because of their understanding of a broad range of biological applications and that the biological engineers should be valuable to industry because of their flexibility and general knowledge.

The importance of developing a consistent and coherent definition of biological engineering and a clear understanding of biological engineering is extremely important in my mind. Both Brockwell and Schembri from the biotech and life sciences industry expressed an uncertainty about what biological engineering is and reinforced the perception that the public is almost totally lacking in understanding of this field. In addition to the development of a compelling definition of biological engineering, it is equally important that the various departments develop curricula, which will educate young men and women to meet a diverse and growing industry.

Johnson [4] wrote in a short and interesting essay:

> It is hard to say whether bioengineering will someday emerge as a separate and distinct discipline. There are many influences from many sources that are tending to keep the field from coalescing as a cohesive unit. Until that happens, there will not be general agreement about a specific knowledge core, courses to offer, or typical academic programs to design. And, without these, industrial or other employers will not be completely sure about the capabilities of graduates from the 90 or so bioengineering programs in the US.

My objective has been to suggest that a coherent knowledge core and courses can be developed to move this process.

CONCLUDING COMMENTS

I am absolutely convinced that biological engineers have to adopt a definition of biological engineering and use it consistently in all of our communications. To do otherwise will add to the confusion and continue to contribute to the fragmentation.

A fundamental question is whether biological engineering will become a science-based engineering discipline (like mechanical engineering, electrical engineering, chemical engineering, civil engineering, etc.) or be an applied area where engineering is applied to biological systems. My bias and conclusion is that biological engineering has the 'DNA' or rational structure to be a well grounded engineering discipline with a mature industry to support its graduates.

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Norman Scott was active in biological engineering research and teaching for over 20 years prior to spending 14 years as a Cornell administrator. His early research was focused on

thermoregulation in poultry, biomechanics of machine milking of dairy cows and electronic applications in agriculture, with particular attention to automatic identification and estrus detection of livestock, as well as the effects of transient current on dairy cows. Since returning to the faculty in 1998, Professor Scott has focused on research and teaching in sustainable development. This research is directed to development of sustainable communities with emphasis on biologically derived fuels, renewable energy, recycling, managed ecosystems and industrial ecology.