Philosophical Foundations of Biological Engineering

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ABSTRACT

Biological engineers apply engineering methods to biological systems. There is a current interest in revising or establishing new biological engineering curriculums and courses. This paper gives a philosophy from which biological engineering curriculums can emerge. Biological engineering should have the conceptual framework of a broad, fundamental, and integrative discipline. Biological engineers should be capable of synthesizing their creations from many disparate sources and. Of communicating with practitioners from many distinct disciplines. Hierarchical competencies are given to distinguish all college graduates, all engineering graduates, and all biological engineering graduates. Basic engineering concepts and basic biology concepts are sometimes conflicting, but must nevertheless be incorporated in undergraduate courses. Specific required courses will vary from university to university, but all biological engineering curriculums must include courses on engineering topics, life sciences topics, and courses that integrate the two. Issues of interfaces between biological engineers and biologists, and with potential employers are also considered. This paper was intended to guide the establishment of new or revised biological engineering programs.

I. INTRODUCTION

Significant changes in biology have occurred in the last forty years. Not only has there been the usual accumulation of scientific facts, but new fundamental knowledge has advanced biology toward a more quantitative discipline. The trend is clear: new means to quantitatively predict biological processes lead to new means to control them. Design of new biologically-based products and processes soon follows. Thus the field of biology has entered the domain of the engineer.

Biology is so broad that the revolution bringing engineering and biological practitioners together has been more like a guerilla war than a coup d'état. There was early linkage between medicine and electrical engineers to produce more effective diagnostic or remedial equipment, that linkage continues. Medicine next obtained assistance from chemical engineers for the design of dialysis machines. Mechanical engineers assisted with orthopedic, prosthetic, and cardiovascular assist devices.

Another branch of biology also began to require engineering skills; the environmental sciences begot environmental engineers, and sanitation, public health, water quality, waste treatment, and bioremediation began to use engineering design and control skills to harness biological mechanisms.

Agricultural engineers have always dealt with elements of biology in their practices.[1] Production of food and fiber requires knowledge of environmental cause/effect relationships, physical properties of biological materials, and human/machine interfacing.

Most recently, genetic manipulation, cellular processes, molecular biology, and tissue culturing have spawned interest by biochemical or bioprocess engineers. Numerous applications in medicine, agriculture, and industry await the development of these kinds of processes and products.

Indeed, the importance of biologically-based processes and products has become so great that convincing arguments have been made that the three basic sciences traditionally studied by engineering students: physics, chemistry, and mathematics, should be augmented with a fourth: biology.[2] All engineers, no matter what their ultimate career objectives, should be exposed in their undergraduate years to the biological sciences. In fact, this is beginning to happen at institutions such as the Massachusetts Institute of Technology.

Beyond the assertion of universal biological sciences exposure, however, each of the engineering applications disciplines of agricultural, biochemical, biomedical, environmental, and others, have struggled with fundamental questions concerning the core of each of their identities. Some of these fields have realized that completion of undergraduate education is not sufficient to produce graduates of great value to employers. Other fields are coming to this realization, and there is a continuing call for the first professional engineer's degree to be at the master's level.[3]

With a recent surge of interest by students and faculties in establishment of curricula that combine engineering with biological sciences, there is a need for definition of undergraduate programs that prepare students for more specific applications training at an advanced level. What should be the educational goals, means to achieve these goals, and relationships to others who share similar goals? The objective of this paper is to present a philosophy for such curricula. Ideas in this paper have been developed from numerous conversations, many published papers, and several workshops devoted to biological engineering educational topics. The philosophies presented in this paper are currently forming the basis for new educational programs in biological engineering.

We present the broadest issues first, starting with the conceptual framework, then moving to a list of competencies expected of all graduates. This leads to essential engineering and biological principles to be included somewhere in the curriculum. Some specific courses to be included are discussed. Finally, two interfacial issues are also discussed: the interface with biologists and the interface with potential employers.

II. CONCEPTUAL FRAMEWORK FOR THE CURRICULUM

While attempting to define the foundations of biological engineering, some statements must be made concerning all of engineering. The biological engineering curriculum should include progressive visions for the entire engineering profession, and this is where we start.

Engineers of the future must become true synthesizers instead of just designers. Computer systems, becoming ever more powerful, will allow repetitive design functions and support to be performed by engineering technologists. As computer systems and software evolve, more and more design problems will become included in the repetitive category.

The functions of engineers will thus change: they will need to know how to incorporate legal, ethical, aesthetic, sociological, environmental, economic, and safety aspects into products and processes.[4] They will be required to assume responsibility for the designs produced by others. Because of these changes, engineers of the future must become more creative, broadly-interested, and basically-trained than their predecessors. They will require the ability to think analogically and comprehensively (analogic thinking is the ability to transfer knowledge from a system that is familiar to a system that is unfamiliar). The ideal engineer should be able to organize and conceptualize, while incorporating additional liberal arts ideas in the creative thinking process.

Obviously, this concept of an engineer contradicts some long-held engineering education principles. There always has been a tension between the hands-on, design-oriented, mechanism-focused approach to engineering education and those who advocate a liberal, philosophical, and creative approach. The present ABET accreditation requirements represent a compromise between these two extremes, but-the incorporation of the humanities is sometimes considered to be an imposition on an otherwise pure engineering curriculum. Although engineering students are educated to think both in a methodical engineering way and also in a more freely artistic way, they are not often given practice to integrate the two. The end product of undergraduate engineering education should be graduates who not only know what the design process is about, but who can also add perspective, judgement, creation, and a sense of the broader needs of society.[5]

This view of engineering underlies the vision for biological engineering that we propose. The biological engineer should be one who can incorporate ideas and concepts from many disparate disciplines into an overall engineering creation. This means that biological engineering should tend strongly toward inclusion rather than exclusion, and that the biological engineer be considered a specialist in technical diversity.

We propose a new undergraduate curriculum intended to produce engineers able to solve problems that bridge between biology and engineering. Graduates must be able to communicate well with both biologists and engineers. To do so, they must be well versed in both the meanings of engineering terms and the specialized language of the biologist. Just as important, these engineers should be familiar with problem-solving approaches used by both groups.

Whereas engineers tend to use physico-mathematical approaches to solve problems, this straightforward technique does not always apply to biological systems. Modem biologists have developed some sophisticated techniques of their own style to deal with the sometimes mandatory indirectness required to solve biological problems. Therefore, biological engineering students should be exposed to biological science courses taught by biologists instead of engineers.

The envisioned undergraduate curriculum is a general curriculum that offers basic instruction in physics, mathematics, chemistry, biology, and engineering. Students should be able to view the full horizon of potential biological applications, from sub-cellular to ecological levels. They need not learn all the details of every application level, but they should not be forced, in the undergraduate years, to choose their eventual specialty. Such a curriculum requires that students be taught commonalities between seemingly disparate biological systems; students should be taught analogic thinking and be given practice in transferring knowledge from one context to another.

Clear definitions sometimes require a statement of what is not included as well as what is included. As envisioned, biological engineering is the discipline of engineering based on the science of biology. "Biological engineers should be to the science of biology what chemical engineers are to chemistry, electrical engineers are to eletricity, and mechanical engineers are to mechanics."[12] Biological engineering does not imply a particular application or industry. In this way it differs from biomedical engineering, environmental engineering, or agricultural engineering, each of which applies knowledge about biology to particular application areas. Indeed, there is even a continuum of engineering involvement with biology, from (for example) the electrical engineer who might work in a hospital environment, to the biomedical engineer who must be able to effectively interact with medical personnel, to the biological engineer whose work requires a substantial and intrinsic knowledge base in the biological sciences. Only the engineer who has a substantial knowledge of, and continuing interest in, the field of biology, should be called a biological engineer.

This proposed undergraduate curriculum is similar in many respects to the general engineering science curricula found at some colleges and universities. It stresses fundamental education at the expense of applications and specialized knowledge. It leads to an . "unfinished" engineer in the traditional sense of engineering education.[6,7] Thus, graduates from this program will require further education before becoming practicing engineers, either by graduate studies or by employer orientation. This is not a novel requirement, nor should it be considered a weakness: engineering science majors have for years made some of the best graduate students, and the generally-educated agricultural engineers have been appreciated by industry for years. Moreover, general education of biological engineers can be excellent background for more specialized graduate study in biomedical engineering, bioprocess engineering (or biochemical engineering, or biotechnology), environmental engineering, agricultural engineering, and other applications of engineering to or with biological systems."

As with any hybrid, it is sometimes difficult to define completely the relationship between the offspring and its parents. Some engineers would say that biological engineers must be engineers first with the biology added later.[10] Others would want equal weighting given to the biological and engineering sciences. While modern biology is too sophisticated to be relegated to the background, engineering can still dominate, as it does in chemical engineering. With such a strong emphasis on biological sciences, the biological engineer may need to team to turn to other engineers for specialized engineering expertise just as she/he must turn to biologists for specialized biological expertise.

There is a great deal of emphasis these days on teamwork,[11] and engineers are required to learn to operate in teams. Industry prefers the type of engineer who can work alongside others with different skills, knowledge bases, and approaches. Working in such teams requires interpersonal and communications skills that engineering must emphasize more than in the past. Inherent in the conceptual basis for biological engineering is the assumption that biological engineers will be working as team members both with biologists and with other engineers.

III. COMPETENCIES

A separate and distinct discipline requires a specialized field of knowledge. Biological engineering can be defined by the expectations required of graduates of its programs. Thus a hierarchical set of competencies has been developed[13] for biological engineering.

The late philosopher, Sidney Hook,[14] has given a suggested list of expectations of all college graduates. Restated, these are:

- Clear and effective communication.
- At least some rudimentary knowledge about the world around and humankind's place in it.
- Some grasp of the principles that explain observations, including a concept of the scientific method.
- An intellectual awareness of the function of society, including historical, economic, and social forces shaping its future.
- An informed awareness of the conflict of values and alternative paths to future solutions.

- Some methodological sophistication that sharpens judgment of evidence, relevance, and validity.
- Induction into the cultural legacies of civilization.

Certainly, there should be a commonality between engineering graduates and other college graduates on these expectations, and the ABET humanities requirements help to ensure that they are fulfilled. To distinguish engineering graduates from all others, the following set of competencies were proposed:[13]

- A well developed ability to conceptualize and fit physical phenomena into a conceptual framework.
- A solid fundamental knowledge of the engineering sciences.
- Reasonable familiarity with computers, computational techniques, and computational aids.
- The ability to carry the design process from problem definition to solution, including the ability to gather pertinent information and deal with incomplete problem definition and aesthetic, reliability, economic, political, ecological, legal, sociological, and general safety constraints.
- The ability to reduce data, concepts, and designs to clear pictorial form.
- The ability to make reasonable engineering assumptions when required, approximate solutions, and produce specific recommendations from indeterminate data.
- A developing sense of engineering ethics and principles by which moral choices may be made within a professional context.

In addition, biological engineering students should also possess:

- A familiarity with at least one specialized biological vocabulary and have the ability to use this vocabulary in effective technical communication with biological, physiological, medical, biochemical, ecological, or applied biological scientists.
- A specialized knowledge of segments of the biological realm, especially problem-solving techniques, related to the biological area of work.
- The ability to deal effectively with uncertainties of biological behavior and properties.
- A generalized knowledge of application of engineering techniques to a broad range of biological subjects, and to be able to develop new applications through analogic conceptualization.

These last four competencies should identify biological engineers from among the remainder of college and engineering graduates. Viewed in this manner, biological engineering education becomes a product of an evolutionary process with many commonalities and some differences from other educational relatives.

IV. BASIC ENGINEERING AND BIOLOGICAL CONCEPTS

Given these competencies expected of every biological engineering graduate, and before required curriculums are defined in terms of new and existing courses, a set of basic engineering and biological concepts can be listed with the expectation that graduates would be familiar with all of them. Such a list can be used to check whether the biological engineering curriculum at any given institution conforms to the expectations of a broad, but fundamental, education.

There are some commonalities and some divergences between traditional engineering science and biological science concepts. Engineering education is largely aimed toward developing the abilities of conceptualization and calculation, whereas biology education develops descriptive and connective abilities. Each of these is important for biological engineers to understand and appreciate.

Engineering concepts that should be included within one course or another are:

- effort and flow variables
- balances
- analogy, equivalence and conversion
- simplicity, parsimony, and incrementality (start simple and add complexity)
- approximation
- calculation
- positive entropy (tending toward disorder)
- reversible and irreversible processes

Fundamental biological concepts are:

- order and negative entropy
- variability
- gradual adaptability
- communication, including patterning
- complex interconnections, simple building blocks
- exquisite control, optimization, and catastrophic failure
- redundancies
- nonlinearity.

There are some concepts that biological engineers must see from both sides. For instance, the physical world tends to disorder, but the biological realm tends to be ordered. Also, engineering solutions tend to use simple connections (such as the development of simple equations or connections to an integrated circuit chip) whereas biological systems usually use complex connections (such as the use of simple sugars, fatty acids, and proteins connected together in a complex way to produce functional biomaterials). Traditional engineering approaches each possible problem from a linear standpoint; biological systems are usually highly nonlinear. There are many other examples that can be given.

Some of the most successful engineering solutions have come from studying existing biological solutions to similar problems. The fields of bionics, biomimetics, and biological cybernetics have contributed in this way. Neural networks illustrate the biological principles of adaptability and redundancy, Velcro connectors illustrate the biological principle of complex interconnections using simple building blocks; modern communications and control are becoming more and more like those of biological systems. Biological systems are such good models for the solutions to many complex problems that the case can be made, if for no other reason, that all engineering students should take at least an introductory course in biology.

V. COMMON COURSES

Engineering science courses add much more detail to the engineering concepts listed in the previous section. Biological science courses do the same for biology. There have been many attempts to define the absolutely essential courses for biological engineering undergraduate curricula,[10,15-18] and many details appearing in these previous reports will not be repeated here because there can be many valid approaches to provide broad, fundamental, and inclusive undergraduate biological engineering curriculums. Most of these reports affirm the usual engineering core courses: physics (especially macroscopic scale), chemistry (inorganic, organic, and biochemistry), calculus (through differential equations), statics, dynamics (some question that this course is required), thermodynamics, strength of materials, materials science (many would opt for more biomaterials and less standard materials), and computer science.

How much biology should be required? Some have said that just one course may be adequate.[19] However, to be an effective biological engineering curriculum, one biology course is not sufficient. Some biological engineering curricula (including the University of Maryland) include up to seven biological science courses; enabling students to take complete biological science course sequences. As many as possible of these biological science courses should be taught by biologists.

At the upper level, engineering courses have been suggested in fluid mechanics, transport processes, biochemical kinetics, instrumentation, control systems, optimization, systems analysis, physiological modeling, material properties, electronics, and communication theory. The ability to deal with biological uncertainty requires some probability and statistics. Upper level courses that integrate engineering and biological systems are essential, and each of these courses should integrate the engineering subject matters with examples drawn from a wide range of biological applications. That is, attempts should be made to expose the students to medical, environmental, horticultural, biochemical, and other possible applications.

Of course, there must be strong components of design and communication in the curriculum. If possible, these skills should be integral to engineering courses.

Humanities courses are essential and must remain part of the curriculum. If possible, material from humanities courses should be integrated into upper-level biological engineering courses. In particular, sensitivity to ethical issues related to living organisms should be developed in upper level biological engineering courses including design.

The philosophy given in this paper envisions biological engineering as broad, fundamental, integrative, and unspecialized. In general, we do not see this approach applying to the graduate level where specialization occurs. Thus, no graduate level courses are suggested.

In a final report of a project sponsored by the United States Department of Agriculture to study curriculum requirements for biological engineers,[19] five core courses were identified for the curriculum. These were: l) Biology for Engineers, 2) Biological Responses to Environmental Stimuli, 3) Transport Processes, 4) Engineering Properties of Biological Materials, and 5) Biological Systems Control. Content descriptions were developed for each of these courses that reflect the philosophy of broad (yet somewhat shallow) treatment of included subject matter. Further USDA funding allowed development of several of these courses, and they are being shared among interested institutions.[20-22] It is intended that all of these courses will be developed eventually if interested and competent developers can be identified.

Young[23] conducted a survey of biological engineering courses at land-grant universities traditionally offering agricultural engineering curricula and their derivative biological engineering curricula. Most courses included in these curricula were upper-level undergraduate courses that included a significant portion of biologically-related material. Course subjects ranged from general to very specific. Many were clearly related to agriculture or food processing, but some were oriented toward biophysics, medicine, or bioprocessing/ biotechnology. The range of courses offered can only increase, but some cohesion is expected to result from the report by Garrett et al.[19]

A similar project sponsored by the National Science Foundation was used to survey undergraduate courses and curricula in biomedical engineering.[24] Courses, as expected, tended to be medically-oriented and less general than biological engineering courses surveyed by Young.[23]

VI. INTERFACING BETWEEN ENGINEERS AND BIOLOGISTS

Forging the new discipline of biological engineering often requires satisfying the concerns of other interested groups. On any given campus, the groups most interested have ranged from other engineering disciplines to segments of the biological science community. Satisfying these groups requires that biological engineers are thoroughly familiar with the position their new discipline is to play in the world of science and technology.

As links between the fields of engineering and biology, biological engineers must appreciate the identities and personalities of both groups. Johnson[25] has identified differences between science and engineering that should be appreciated by both sides. There are three different perspectives to consider: 1) phylogeny, 2) motivation, 3) methods.

A. Phylogeny

The evolution of technology usually occurs with at least four distinct phases: 1) A random phase where events occur by chance and observation occurs haphazardly. The major outcome of this phase is to make the observers aware of the phenomenon being observed. 2) A descriptive phase where cause and effect relationships are established. The result of this phase is that the observed phenomenon no longer remains random, but can be expected whenever a series of foretold events happens. The phenomenon is still not able to be brought about at will, but its appearance is at least expected. 3) A quantitative phase wherein measurements are refined and dependencies are given numerical values. These values may be deterministic or probabilistic, but during this phase there is a growing knowledge about the intensity of the phenomenon as related to the strength of the precursor variables. 4) A control phase where modeling and predictive equations lead to knowledge of useful substance amounts, design of systems, and applications to achieve desired ends. The result of this stage are products and processes using the phenomenon. Examples are given in Table 1.

For some sciences, the early phases began long ago. The science of mechanics, for example, entered its descriptive phase before the time of Aristotle, but the science of electricity was still partially random in the time of Ben Franklin and the science of genetics entered a long descriptive phase in the time of Gregor Mendel.

The first two of these four phases clearly belong to the field of science. Engineering contributes primarily in the control phase by using quantitative information to design useful products. The overlap between science and engineering generally occurs during the quantitative phase. Early attempts at quantification are largely made by scientists, but engineering researchers, usually motivated by the need for design information, can accelerate the quantitative process. Engineering is involved more with the latter stages of technology than with the earlier stages where science dominates.

Phase	Description	Physical Example	Biological Example
Random	Phenomena are Encountered haphazardly.	Heavenly bodies are observed to move.	Difference and Similarities are noted in animals and plants.
Descriptive	Cause and effect relationships are Established.	Apparent heavenly movement appears to be related to seasonal changes.	Genetic material is discovered and transgenic organisms are developed.
Quantitative	Measurements are refined and dependencies are given numerical values.	Kepler's laws describe planetary motion.	Optimal microbial growth environments are determined.
Control	Modeling and Predictive equations lead to knowledge of useful substance amounts, design of systems, and applications to achieve desired ends.	Satellites are orbited around the Earth, moon, and other planets.	Transgenic microbial production of biochemicals become reality.

B. Motivation

Scientists and engineers can both be highly motivated, but the sources of work-related interests are often different for each group. Neglecting the recent trend toward entrepreneurship in both groups, the major source of motivation and satisfaction for engineers comes in the final products or processes as a result of their efforts. Engineering is largely creative, forming things that never were, and engineers, like artistic painters, become highly motivated by the tangible realization of their ideas and concepts. If, in addition, there are visible groups that can be helped by these realizations, a strong drive and sense of urgency can develop within the engineer.

Biologists, generally more removed from the ultimate applications of their work than are engineers, are often motivated by the subjects of their study. They feel empathy toward these subjects, and study them because they are interested. This study, of course, leads to more interest, and a strong bond can develop between the observer and the observed. Biologists are thus motivated more by their involvement with their subjects, and engineers by their involvement with the things they produce.

C. Methods

There is a fundamental difference in methods used by scientists and by engineers. Biological scientists often perform experiments to ascertain new facts. Since many of their observations are related to phenomenon description, the pattern of scientific experimental episodes may be determined more by the observed phenomenon than by any regular scientific plan. Such is often the case while observing various life-forms in their natural habitat: observations about eating only occur when the object of the attention decides to eat. Any attempt to tamper with the behavior of the being would result in criticisms of methods and observations, rendering them practically invalid.

Engineers rarely, if ever, become involved with their experimental objects at the descriptive phase, and hence are often remote from these types of experiments. The impatience of most engineers would not allow them to observe phenomena without trying to tinker with the experiment to see what happens. Engineers are not educated to be distanced, impartial observers; they are educated to become involved, to attempt to predict or control an outcome, and to synthesize fragments that may not naturally fit together.

There is a difference between typical scientific literature and typical engineering literature. Scientific experiments beyond the completely descriptive phase are conducted. for specific sets of conditions, with -as many variables controlled as possible. To cover an entire scientific field with scientific observations requires a very large number of specific experiments, wherein control over the multitude of variables may be either tightened or relaxed, but many, if not most, combinations of imposed conditions must be tested before a phenomenon is considered to be well-understood.

There are very few, if any, surprises appearing in scientific papers of this sort, and these papers have scientific value by extending the realm of the known by additional increments. The differences between scientific papers, cited and uncited, related to a particular field are often few, and they all form a congealing mass that establishes scientific truth by the weight of consistency of experimental results.'

Science, therefore, is inductive. Scientific facts accumulate until an overall unifying concept emerges as irrefutable. The conceptual framework is induced, in science, from the many facts that precede it. The engineering approach is different. Engineers generally try to conceptualize first and fit facts within this established framework Engineering is thus deductive.

This method suits engineers well, because it tends to reduce all knowledge to a small set of fundamental principles: the conservation of matter and energy, Newton's laws of motion, the laws of thermodynamics, and Maxwell's equations are among these. Engineering designs are thus based upon a rather limited set of simple principles, or concepts. Given the choice between one of these fundamental principles and a conflicting fact, the principle is nearly always chosen by engineers.

Such a fundamental methodological difference between scientists and engineers inevitably leads to conflicts. Scientists are often bothered by the engineer's tendency to simplify, while engineers wonder why scientists can't see readily-apparent connections.

Starfield et al.[27] state that mathematical models are like caricatures: they overly emphasize some aspects at the expense of others to make conspicuous those results due to the emphasized aspects. Thus, models are not always general descriptions of a phenomenon. Indeed, a thorough mathematical description of some scientific phenomenon would be as complicated as the original phenomenon itself, and serve very little purpose. It is often difficult for a scientist to truly believe what value is contained in a model that does not predict all scientific observations related to a particular phenomenon.

D. Synthesis

Although science and engineering are separated by dominant domain, methodology, and approach, engineering is complementary to science and science is supplementary to engineering (Table 2). Engineering represents the ultimate application of the facts generated by science. And, engineering approaches are having their effects on scientific methods. Science, on the other hand, not only discovers the basic phenomena that are the subjects of later engineering models, but science also discovers pertinent variables for inclusion in those models.

Relative merits of experimental and conceptual (or model) approaches to a scientific phenomenon are well known. Each approach is so compelling that the ideal means to study the phenomenon is to incorporate both approaches. It is the willingness of scientists over the last 30-40 years to include modeling and conceptualization in their work that has enabled the rapid application of scientific knowledge by (usually) engineers.

Although biological scientists are often capable of generating the information necessary for the design of a new product or process involving a biological system, they don't often deliver the information in a form suitable to make design trade-off decisions. Biological engineers are in positions to function as key participants in the synthesis of biological science and engineering to produce results useful to humankind.

VII. EMPLOYMENT

As general engineers who often require further training in specific applications, biological engineers may not be completely prepared to step into positions that require immediate engineering output. Nonetheless, employers who realize the strengths possessed by biological engineering graduates (notably their abilities to work with biological scientists and to work in team situations), often become enthusiastic about hiring them.

	Science	Engineering
Phylogeny	Random phase through quantitative phase	Quantitative phase and control phase
Motivation	Objects of study	Objects of creativity
Methods	Inductive: large numbers of facts suggest a unifying concept	Deductive: a small set of basic principles leads to specifics
Literature	Incremental	Conceptual
Synthesis	Scientists need engineers to show eventual applications	Engineers need scientists to identify basic facts

Table 2. Summary of contrasts between science and engineering

Not all biological engineers will pursue graduate schooling. It is still too early to tell exactly how much employment potential exists for biological engineers terminating their schooling at the bachelor's level. Nonetheless, there are several courses of action that can be taken to boost employment demand at the B.S. level. The first is to avoid a curriculum that is too specialized. B.S. biomedical engineers have often been seen as too specialized in medicine and not enough in engineering skills to be readily employable. The biological engineers we envision, while probably comparable to biomedical engineers in engineering skills, should be more readily employable because of their familiarity with a broad range of biological applications. These engineers should be valuable to industry because of their flexibility and general knowledge.

The second course of action is to depend heavily on experiential learning_in the undergraduate years. Internships and cooperative education are very important to successful employment of B.S. biological engineers. Employer relationships developed in the process of establishing internships or cooperative employment will lead to greater interest by employers in both the curriculum and its product.

A study by Johnson and Rehkugler[8] projected that there will be an annual total of about 2000-3000 biological engineering employment opportunities in various specialty areas by the year 2000. These specialty areas include agriculture, animal systems, aquaculture, bioprocessing, biotechnological systems, ecology, environment, food, horticulture, human interfacing, medicine, microbial systems, and rehabilitation engineering. Some of these specialty areas require additional formal education to gain admittance, while others do not.

A survey of potential employers of biological engineers was conducted by Hoffman.[28] The list includes 288 entries, and many employers were eager to hire biological engineers from particular programs. This would indicate that the biological engineering programs are producing the types of graduates needed by employers, and gives confidence to faculties that their efforts are related to the reality of the workplace.

VIII. CONCLUSIONS

Biological engineering curricula are presently being revised or established on many campuses in the U.S. and Canada. In this paper we have attempted to define important parameters for these curricula. It is usually much easier to establish a new structure if the plans have been drawn beforehand. The function of this paper was to supply the blueprint. Students trained along the lines given herein will have the ability to satisfy present employer needs as well as to meet challenges of the future.

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