Biological Engineering Evolution

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INTRODUCTION

Engineering is a practical art learned from scientific knowledge, mathematical logic, and experience from practice. Over the past 5000 years, engineering has evolved into the means by which ideas are turned into useful products, process, and systems, thus contributing to the development of technologies that have helped the society to advance and prosper. In other words, engineering meets societal needs. Perhaps engineering, as an attempt to design methods for the use and control of natural materials, began with the beginning of civilization itself.

This chapter presents a brief history of engineering and the evolution of several engineering disciplines. Biological engineering, the newest engineering disciplines, is in a nascent stage. The growth and potential of biological engineering in the age of information and biology is discussed.

EARLY ENGINEERS

As early as 6000 B.C.E., ancient Mesopotamians (inhabitants of the land between the Tigris and Euphrates rivers in the present-day Iraq) built temples, water canals, city walls, and significant irrigation and flood control systems. Ancient Egyptians, whose work in building large structures is legendary, also developed extensive water transporting canals and drainage systems. Similarly, engineering feats of the Greeks and Romans include extraordinary temples, extensive networks of roads and bridges for transportation, aqueducts, and the development of construction methods and machines (such as pile drivers, hoists, and bucket wheels for lifting water) and building materials. Without the present-day knowledge of the natural sciences, these "engineers" must have relied upon intuition developed from an acute sense of observation rather than on a critical understanding of the laws of nature and mathematical logic.

Advances in science and mathematics in the Middle Ages (1300–1700 A.D.) spurred the development of science-based engineering principles and practices. These principles and practices constitute a body of knowledge known as engineering science. Engineering science gives a fundamental basis for engineering work, provides an objective basis for evaluating the functionality of design concepts and enables the prediction of behavior in designed systems under anticipated "operational" conditions. The science of engineering evolved with the use of mathematical logic to interpret natural laws and to provide objective principles for engineering design. The discoveries of Copernicus, Galileo, Boyle, Hooke, and Newton were useful for the advancement of engineering science as they contributed to the development of subjects such as statics, dynamics, fluid mechanics, and heat transfer—all of which are part of the canon of engineering science.

CIVIL ENGINEERING

Over the centuries, many branches of engineering have evolved. Initially the primary focus of engineering was on designing machines for the military and for the construction of structures. Englishman John Smeaton is credited for coining the term "civil engineering" in 1761 to describe a type of engineering undertaken for the development of civil society, thus distinguishing it from military engineering with the primary focus on war and destruction. The oldest of all the branches of engineering science, civil engineering continues its original focus today, encompassing a wide range of engineering activities related to structures, roads, bridges, water systems, flood control, protection from adverse environmental conditions, and sanitation. The British established the Institution of Civil Engineers in 1818. The American Society of Civil Engineers was established in 1852.

MECHANICAL ENGINEERING

Advances in the design of the English blast furnace played a key role in the beginnings of mechanical engineering. The blast furnace was used to process iron ore, an essential element in the production of high quality wrought iron and steel. The greater availability of high quality steel provided materials for designing new machines and manufactured products. The profession of mechanical engineering experienced its fastest growth during the Industrial revolution of the 18th and 19th centuries. A wide

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variety of machines were needed to manufacture goods and provide power to fuel emerging industries. Today, mechanical engineering is a broad-based engineering discipline with a focus on mechanisms, machines, and power generation. The fundamental principles of classical mechanics and thermodynamics from physics and mathematics provide the basis for mechanical engineering. The British established the Institution of Mechanical Engineers in 1847. The American Society of Mechanical Engineers was established in 1880.

ELECTRICAL ENGINEERING

The beginning of electrical engineering is associated with the need for electricity to power machines, devices, and industries that were being developed by mechanical engineers. The fundamental principles of electro-magnetic phenomena and mathematical logic are the basis for electrical engineering. With a wide range of applications for advanced technologies in power generation and transmission, communication, instrumentation and measurement, electronics, computers, and controls, it is not surprising that electrical engineering has become the largest branch of engineering. One of the fastest growing areas in electrical engineering is electronics engineering that exploits emission, behavior, and effects of electrons for designing efficient electrical devices. The Institute of Electrical and Electronics Engineers was established in 1884, four years after Thomas Edison's invention of a practical incandescent bulb and two years after the first electric generating station on Edison's Pearl Street in New York.

CHEMICAL ENGINEERING

Advancements in manufacturing during the late 1800s precipitated the need to understand chemical changes in materials during industrial operations. Such changes became an important consideration in the design of processes in industrial plants. Thus, the principles of chemistry and a quantitative understanding of distillation, heat and mass transfer, reaction kinetics, and extraction gave rise to the discipline, of chemical engineering. Today chemical engineers are involved in the design of biochemical processes for the production of useful products such as food, fuels, and pharmaceuticals. In 1908 the American Institute of Chemical Engineers (AIChE) was established.

Within a 100-year period, starting at the beginning of the nineteenth century, four engineering disciplines (civil, mechanical, electrical, and chemical) made major advances and established professional societies to further the disciplines and profession of engineering. These engineering fields started with an application-focused orientation in order to fulfill the societal needs of the time. At the same time, advancements in physics, chemistry, and mathematics provided careers in engineering research that began formulating engineering principles and practices for the foundation of engineering science. With the advent of engineering science, these engineering fields began to transform from application-focused studies to science-based disciplines. This transformation liberated these engineering disciplines from the confining perspective derived from the application needs of limited areas. Thus, these engineering disciplines are now viewed as fundamental fields of engineering that are application-independent, i.e., their work is applied to all areas where designed products, processes or systems are useful. (Note that in the evolution of science-based engineering disciplines the two components of natural sciences, physics, and chemistry, have been the knowledge-pool for developing engineering practices and principles. However, biology has contributed a very limited input or perspective. Interaction between engineering and biology has been limited at best. This has been dealt with in the later part of the chapter.)

MINING, METALLURGICAL, AND PETROLEUM ENGINEERING

The nineteenth century saw the rise of several new areas of engineering focused on meeting societal needs. These areas included designing systems for the extraction of raw materials deep inside the earth (mining); designing systems for producing materials (mostly metals) with properties desired for the many products of industrial production (metallurgy); and designing systems for extracting and refining petroleum to satisfy the increasing energy appetite of industry and the growing demands of society for machines and appliances of convenience. These engineering needs were so important and widespread that in 1871, even before the establishment of the American Society of Mechanical Engineers (in 1880), the American Institute of Mining, Metallurgical and Petroleum Engineers was established and became the second engineering professional society in America to be formed after the American Society for Civil Engineers.

AGRICULTURAL ENGINEERING

One of the most important engineering challenges at the beginning of the 20th century was to meet the needs of agricultural mechanization. There were two powerful forces driving this need: 1) more than 95% of Americans lived in rural farm communities and technologies that relieved farmers from hard work in extreme outdoor conditions became a primary national need and 2) the establishment of new industries was dependent on a large supply of workers and the only additional indigenous source of labor was found in rural and farm communities. Thus, in addition to their work producing food, farm laborers were needed to help support the industrial revolution. The only solution was to increase the productivity of farmers by the use of technology, thereby freeing them to work in new industries. The field of agricultural engineering began evolving at the end of the 1800s and in 1907, one year before chemical engineers organized their professional society, the American Society of Agricultural Engineers (ASAE) was established by pioneers who were devoted to designing systems for reducing the time and drudgery involved in agricultural production. Today, one farmer produces enough food for more than 100 people and more than 97% of Americans are involved with nonfarm related work. (The 20 "Greatest Engineering Achievements of the 20th Century," a project launched by the National Academy of Engineering in 2000, named Electrification as the greatest engineering achievement of the past century and Agricultural Mechanization the seventh—agricultural engineering played a key role in both.)

An important observation in the evolution of agricultural engineering as a discipline is that unlike mechanical, chemical, and electrical engineering (that transformed from their initial application-focus to science-based engineering disciplines), agricultural engineering has largely remained unchanged and continues to be focused on application to agricultural systems. By the late 1960s, with the mechanization of agriculture nearly complete, there was a sharp decline of interest in agricultural engineering.

Attempts began in the early 1970s to transform the agricultural engineering discipline by enlarging its application domain to include new but related areas of postharvest, food, natural resources, and the environment. In many ways, these new areas are logical extensions of agricultural engineering as they are inherent components of "agriculture" itself. However, other emerging engineering disciplines focused singularly on each of these areas. Food engineering and environmental engineering, e.g., attracted engineers from the science-based disciplines of chemical, mechanical, and electrical engineering to these agriculturally-related application fields.

Unlike the agricultural engineering of the past when the discipline had sole dominion over agricultural mechanization, the changes of the 1970s brought several other players to the agricultural field of application. The growth of agricultural engineering in new application areas was slower than the attrition due to lack of interest and low national priorities placed on farm efficiency. By the mid-1980s the profession began to exhibit serious decline and by the later part of the decade the rate of decline became alarming. Several academic programs had unacceptably low enrollments and were on university administrators' short list for elimination. Similarly research programs in agricultural engineering were barely recognizable in the USDA's national priorities. Membership in ASAE declined precipitately.

BIOLOGY AND ENGINEERING

A revolution in the field of biology began in the mid-1950s. Starting with the discovery of double helix, an incredible understanding of genetics and the functions that govern life processes at the molecular level has been gained. In the 1980s, scientists were able to successfully engineer living systems that express desired behaviors at the genetic level. Many call this type of work genetic engineering. The approach used by genetic engineers to design living systems is similar to that used by mechanical engineers, as the goal of both disciplines is to conceptualize and build systems that satisfy a specific need. The difference is that mechanical engineers, e.g., employ their knowledge of mechanics and other principles from physics in their design work, where genetic engineers use their understanding of genes and gene functions.

For the past several years, genetic engineering techniques have been successfully used to develop pest-resistant plant varieties. Today, genetic engineers have developed sophisticated cloning methods that enable the creation of complex life forms such as sheep, cows, and pigs. In addition to bioengineered plants and animals, the new discipline of biological engineering is also being used to develop pharmaceuticals and other useful products and processes designed to meet the needs of society.

Advances in biology are leading to the creation of useful methods for designing life forms. For example, biologists are gaining a new understanding of living systems and employing this new knowledge (through trial and error methods) to design systems at the molecular level. While the work of these biologists shows great potential, there is an equally fervent effort to develop the discipline of biological engineering by using an application-focused approach. The two primary areas of application are agriculture and medical and health systems. On this front, biomedical engineers are focusing their work on the design and creation of useful products, such as biomaterials and artificial organs that are able to perform the functions of living tissues and organs.

To a great degree, the trial and error methods of biologists are similar to those of the early designers in

Mesopotamia who created complex systems by intuition and experience using limited scientific and mathematical (objective) logic. However, engineers designing systems for agriculture and medicine are employing greater mathematical logic in their designs. These engineers have been greatly handicapped, as the scientific understanding of biology has been largely unamenable to[F1] classical mathematical formalism. Today, engineers, biologists, mathematicians, computer scientists, and statisticians are actively engaged in developing computational methods that describe the processes of living systems. These computational methods are allowing "mathematical" (objective) logic to be used in biological engineering design.

SCIENCE AND ENGINEERING

Fig. 1 is a schematic illustration of the perspectives of science and engineering, and their relationship in the design of products, processes, and systems. Although the role of cultural values in design was not discussed earlier, it plays a very important role in the work of engineers and is included in the illustration.

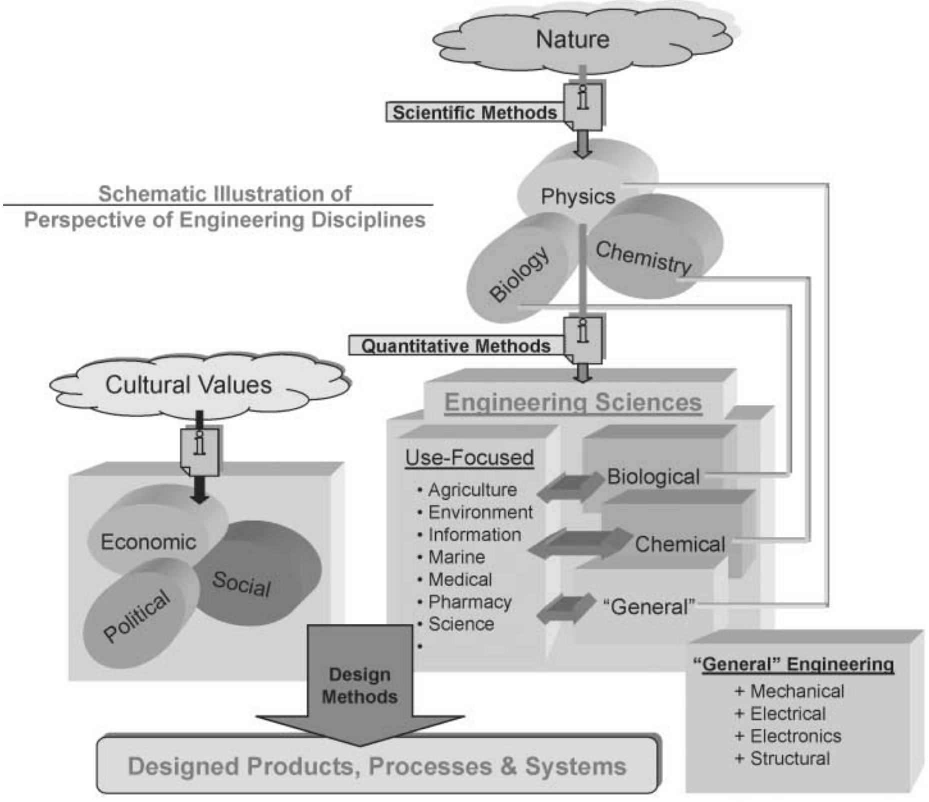

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Fig. 1 Schematic illustration of interrelationship between science and engineering. The knowledge of the three components of natural sciences (Physics, Chemistry, and Biology) is discovered by critical inquiry (shown with i) of nature by using the Scientific Methods. Similarly, principles of Engineering Sciences are gained by critical investigations (shown with i) of natural sciences using Quantitative Methods of mathematical and computational sciences. The direct connections between Physics to General engineering, Chemistry to Chemical engineering, and Biology to Biological engineering show the fundamental sources knowledge of the three Engineering Sciences. The knowledge of the three engineering sciences is used to develop principles useful to the application (Use-Focused) areas, such as Agriculture, Environment and others. (See bidirection arrows in the engineering science box indicating this relationship.) Engineering Sciences for the Use-Focused areas often have customized principles and practices that evolve from experience and intuitions gained from the designing experience of engineers. The knowledge of Cultural Values (Social, Economical and Political) are critical to create successful and useful designs. Design Methods a systematic process that employs knowledge from sciences and cultural values for Designing Products, Processes and Systems beneficial to the prosperity of society.

Fig. 1 shows that the study of nature (with the use of proper research methods) leads to the discovery of knowledge (by revealing the laws and governing observations on how natural systems work). For simplicity, "nature" was reduced to three components: physical, chemical, and biological (reflective of the natural sciences). In reality, however, nature is an integrated whole and cannot be so reduced.

Engineering sciences provide the principles and practices necessary for creating successful designs. Knowledge of the natural sciences is fundamental to the development of the engineering sciences, and objective logic (mathematical and computational methods) is critical to transforming scientific knowledge into engineering principles and practices. This connection is shown in Fig. 1. For example, the earliest scientific understanding of physics gave rise to the "general" engineering sciences that provide the overall perspective and framework for engineering science itself. Similarly, the discipline of chemical engineering is developed from chemistry. The inability to understand complex living biological systems and the absence of developed objective logic has been impediments in the evolution of biological engineering. With recent advances, however, biological engineering is developing but is still in a nascent stage.

All engineering work is undertaken for the central objective of creating new and useful designs. Fig. 1 shows that the knowledge of general, chemical, and biological engineering sciences has to be applied for designing useful solutions to societal needs. Agriculture, pharmacy, and medicine are just a few examples of application-focused engineering disciplines that are developing from both the knowledge of science and the intuition of practitioners. The bidirection arrows between the science-based and application-focused areas are important. Without this interaction, engineering science is mute to society's needs.

Finally, Fig. 1 illustrates that cultural values are an integral part of engineering design. A perfectly viable technical design is useless if it does not fit into a society's value system and fulfill a societal need. Fig. 1 shows that the successful design of products, processes, and systems is a result of the proper use of scientific and cultural knowledge in engineering design methodology.

In summary, biological engineering is evolving both in terms of its knowledge-base, applications, and methodologies. Scientists, e.g., are advancing the understanding of biology using trial and error methods, engineers in several engineering disciplines are designing application-specific systems and computational scientists are developing quantitative methods for biology. Furthermore, there is growing evidence that new engineering design methodologies may emerge from the new understanding of living systems. Advances on all of these fronts are needed to contribute to the development of the biology-based engineering science.

ENGINEERING DISCIPLINES IN THE AGE OF BIOLOGY

In the decade of the 1990s, engineers from all disciplines have carefully assessed the role of biology and have made visible attempts to incorporate biology into the work of their respective engineering fields.

Biological Engineering and Agricultural Engineering

To the agricultural engineering discipline, the debate on the role of biology is an old one. As early as the 1930s, a small group of visionaries in ASAE led by Ohio State University Professor C. O. Reed, argued vehemently but unsuccessfully that the discipline of agricultural engineering is based not on the application of civil, mechanical, and electrical engineering to the industry of agriculture but on the science of biology; "it is the engineering of biology." This profound shift in the perspective of agricultural engineering in the 1930s from application-focused to science-based engineering would have led the discipline to a different course. With the death of Professor Reed in 1940 this argument became dormant and would not surface again until the beginning of 1960s.

In the 1960s, Wilson B. Bell, an agronomist and administrator at Virginia Agricultural Experiment Station awakened agricultural engineers by stating that, "Your sphere of activity is more closely intertwined with the life sciences ... You cannot escape, even if you wished, the world of living things." Professor Wallace Giles of North Carolina (N.C.) State University led this discussion and spoke widely for a biology-based engineering discipline. An ASAE Committee appointed in 1962 headed by another professor from Ohio State University, Robert Stewart, did not support the advancement of agricultural engineering as a biology-based engineering discipline, but instead recommended the formation of a division of biological engineering in ASAE to heighten the use of biology in the work of agricultural engineers. Despite the committee's recommendation, ASAE formed a bioengineering technical committee. N.C. State University changed its name to Biological and Agricultural Engineering in 1965 and became the only department in the country with a name other than agricultural engineering. It was only a year later that Mississippi State University took heed to these changes and became the second department in the country to change its name to Agricultural and Biological Engineering reflecting the added biology-focus in the department's work. In 1969, Mississippi State University became the first and the only department to offer a separate undergraduate degree program in biological engineering based on the science of biology. The pioneering program educated students to apply biological engineering to a range of areas including medicine, agriculture, environment, and veterinary. Other than N.C. State University and Mississippi State University, there was little interest was shown by other universities, and industries were not supportive to modify the professional content of agricultural engineering.

For the next decade and a half, the issue of biological engineering was not a national debate among agricultural engineers. However, there were several departments actively experimenting with adding biology and biological science perspective to agricultural engineering. In 1987, at the Conference for Administrative Heads of North American Agricultural Engineering Departments in Columbus, Ohio (the home of the late Professor E. O. Reed who had in the 1930s argued unsuccessfully that agricultural engineering should be viewed as "the engineering of biology"), the potential of biological engineering was identified. Three years later in 1990, the ASAE Academic Program Administrators Committee developed a "Vision of the Future" with four recommendations: 1) offer a biological science based, biological applications focused engineering curriculum that defines our uniqueness among engineering disciplines; 2) have a core curriculum designed to define the biological science base of our discipline; 3) provide areas of emphasis within the curriculum that focus upon applications involving biological systems; and 4) adopt "Biological Engineering" as the name of our curriculum.

Work throughout the past decade provided a much greater understanding of the role of biological sciences in the discipline of agricultural engineering. The 1990s was a decade of profound debates in ASAE and in academic departments. From the mid-1980s, Professor Norm Scott of Cornell University championed the argument for biological engineering in the ASAE. During his term as the President of ASAE in 1993–1994, Scott called for an active debate and asked how ASAE should change to capture the promise of biological engineering. This debate led to the establishment of the Institute of Biological Engineering (IBE) in 1995 with the objective "to encourage inquiry, application, and interest in biological engineering in the broadest and most liberal manner and to promote the professional development of its members." ASAE agreed that IBE should have autonomy in membership, programs, and services normally available to an independent professional society. They saw that they could benefit from the new class of IBE members who would otherwise not be attracted to their organization (which was a great incentive during the rapidly declining membership) and IBE founders recognized the opportunity to provide a scientific and professional forum for the rapidly growing discipline of biological engineering. Although the leadership of ASAE was very supportive of this arrangement, many prominent and active members of ASAE were uncomfortable with the ASAE/IBE relationship. ASAE found the new arrangement difficult to implement. On December 28, 1999, IBE separated from ASAE and became an independent professional society.

The 1990s were also a period of great advancement for the ASAE. Many departments began to appreciate the value of incorporating biology (some say agro-biology) and a biological science perspective to the discipline of agricultural engineering. Others moved to this position because of the alarming decline in student enrollment. Major efforts were undertaken both locally and nationally to reevaluate curriculum. By the end of the decade, all agricultural engineering departments in the United States, with the exception of one, added "biosystems", "bioresource", "biological", "food," and/or "environment" with "agricultural" to their names. A few departments went as far as completely dropping the word "agricultural" from their name, citing the argument that new titles such as "biosystems" inherently include agricultural systems. By the mid-1990s, even the ASAE, the professional society that had been home for "agricultural" engineers, changed its marketing strategy at the recommendation of a presidential commission and started promoting itself by its abbreviations "ASAE." The organization added a byline to read "The society for agricultural, food and biological systems." When IBE became a separate professional society, ASAE membership excitedly formed a division of biological engineering at the 1991 Annual Meeting. Today, the ASAE division of biological engineering has undertaken the application perspective for the areas of agricultural, food, and biological systems, and the IBE continues its vision to be the "headquarters" of the application-neutral biological-science based engineering discipline evolving from the advances of biology.

Biological Engineering and Biomedical Engineering

The two engineering societies, active in advancing biological engineering from the application in medicine perspective are the Biomedical Engineering Society (BMES) and the Institute of Electrical and Electronics Engineering–Engineering in Medicine and Biology Society (IEEE–EMBS). The stated purpose of BMES is "to promote the increase in biomedical engineering knowledge and its utilization." BMES addresses only a single but a critical application area of medicine that is essential for the prosperity of society. It was established in 1968. BMES has seen a phenomenal growth in the nineties with the advances in biology and medical technologies. It has also benefited from the Whitaker Foundation's generous support for developing biomedical engineering and the increasing priority in the United States and increase in the research budget of the National Institutes of Health (NIH).

IEEE–EMBS is similarly focused on medicine but with a more interest in biology as well. IEEE is the primary home of electrical engineers. EMBS being a part of IEEE has evolved from the perspectives of electrical engineering. Its stated interest is "The field of interest of the IEEE-EMBS is the application of the concepts and methods of the physical and engineering sciences in biology and medicine. This covers a very broad spectrum ranging from formalized mathematical theory through experimental science and technological development to practical clinical applications. It includes support of scientific, technological, and educational activities."

BIOLOGICAL ENGINEERING AND CHEMICAL ENGINEERING

There are many academic departments adding biology to the chemical engineering program. Perhaps the recent change of MIT is indicative to the evolution of biological engineering in the field of chemical engineering. MIT states that biology is not only amenable to, but requiring engineering analysis and synthesis design approach has formed a division of biological engineering. American Institute of Chemical Engineers has been organizing many biologically engineering related technical sessions in their annual meetings. Now there is an active move to form a biological engineering division in the AIChE.

BIOLOGICAL ENGINEERING AND MECHANICAL ENGINEERING

Mechanical engineers have been active in the development of devices for the medical and health industries. They are contributing to engineering science knowledge in such fields as biomechanics, biofluid mechanics, heat and mass transfer in biotechnology and cell and tissue engineering are mechanical engineers. The American Society of Mechanical Engineers has a Bioengineering Division which is "focused on the application of mechanical engineering knowledge, skills, and principles from conceptions to the design, development, analysis, and operation of biomechanical systems."

CONCLUSION

Engineering is a practical art learned from scientific knowledge, objective logic, and experience from practice. Over the past 5000 years, the science of engineering has evolved to meet the continuously changing needs of society. Many disciplines of engineering have evolved by first focusing on designing products for a clearly identifiable need of society. A few of these engineering disciplines (mechanical, electrical, and chemical) have evolved into science-based disciplines drawing its fundamental engineering understanding from the knowledge of natural sciences. Other disciplines have remained primarily application focused (e.g., agricultural engineering to the industry of agriculture).

Biological engineering is evolving from both directions. Many scientists are intimately involved in designing new living systems by using advancing knowledge of biology at the molecular and genetic levels and some objective logic. These designs are results of trial and error approaches. They are contributing to new engineering principles of biological engineering. Simultaneously, those engineers who are primarily focused on application and are designing new systems for the agriculture, medical, and health industries are developing practices of biological engineering. Together biologists and engineers are evolving a new science-based engineering discipline—the biological engineering. The 21st century will make incredible advances through the evolving discipline of biological engineering which will make the advances of the 20th century look elementary.

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Some Useful Websites

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American Society of Agricultural Engineers: http://www.asae.org/about.html

American Institute of Chemical Engineers: http://www.aiche.org/

American Society of Mechanical Engineers: http://www.asme.org/divisions/bed/

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IEEE Engineering in Medicine and Biology Society: http://www.eng.unsw.edu.au/embs/index.html