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The Descent of Biological Engineering*

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The genealogy of Biological Engineering, spanning a period of at least four millennia, shows that Biological Engineering is descended from the intersections of various disciplines that originate from three ancient pillars of knowledge, including the practices of engineering and medicine and the discipline of philosophy. The descent of Biological Engineering through the ages flowed from the demise of Teleology and from the triumph of Mechanism, making Biological Engineering a thoroughgoing mechanistic discipline, no different in this respect from all the other modern engineering disciplines. It is the mechanistic nature of Biological Engineering that enables the basic technical activity of Biological Engineering, engineering design, to be successfully accomplished. The genealogy of Biological Engineering also underscores that, based on historical evolution, Biomedical Engineering precedes Biological Engineering. Based on the disciplinary hierarchy, however, Biomedical Engineering falls under the rubric of the broader, more inclusive, Biological Engineering.

Keywords: biomedical engineering; biological engineering

INTRODUCTION

THE VENERABLE *Encyclopaedia Britannica* defines 'Bioengineering' or Biological Engineering as 'the application of engineering knowledge to fields of medicine and biology' and lists its application areas as 'Medical Engineering, Agricultural Engineering, Bionics, Biochemical Engineering, Human Factors Engineering, and Bioenvironmental Engineering' [1]. Cuello [2, 3] defined Biological Engineering as the engineering discipline whose science base is biology, in the same way that civil and mechanical engineering have mechanics (physics), electrical engineering has electricity (physics), and chemical engineering has chemistry as their science bases, respectively. Operationally, Cuello [4] defined Biological Engineering as the optimization of a task or set of tasks performed by or upon a biological system through application of the engineering design process. This operational definition establishes the basic precept that, similar to all other engineering disciplines, Biological Engineering focuses on the engineering design process as its basic technical activity across its application domains [4, 5]. Today the Institute of Biological Engineering defines Biological Engineering as '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 aim of this paper is to trace the descent or lineage of Biological Engineering through time from its various disciplinary sources, seeking insights into its fundamental philosophical foundations.

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ANCIENT BEGINNINGS: THE ADVENT OF TELEOLOGY

The genealogy of the various disciplines that led eventually to the melding of engineering and biology in the 20th century covers a time span of at least four millennia, dating from as far back as circa 3000 BC. At around this time, three pillars of knowledge served as foundation stones for the gradual rise of the modern sciences and the subsequent, or perhaps inexorable, convergence of engineering and biology. These three pillars were the ancient practices of engineering and medicine plus the discipline of philosophy. Figure 1 illustrates the genealogy of Biological Engineering, showing the significant intersections of the various relevant disciplines leading to its genesis.

Medicine and engineering in ancient times were patently not scientific disciplines. While ancient engineering was part trial-and-error and part handed-down knowledge [6], ancient medicine was part trial-and-error and a large part superstition [1]. The first practicing engineer on record was Imhotep, who was chief minister for the Egyptian pharaoh Zoser around 2750 BC and was credited with building one of the first pyramids of Egypt, the Step Pyramid at Saqqarah [7]. It is noteworthy, if also surprising, that the first practicing physician on record was also Imhotep, who also served as court physician at the time [7]. Since the earliest practicing engineer and the earliest practicing physician in recorded history were the same person, one might imagine that only a short time would elapse before engineering and medicine would merge to give rise to Biomedical Engineering. As it happens, more than four thousand years had to pass before such disciplinary fusion would occur.

The march of ancient engineering and medicine

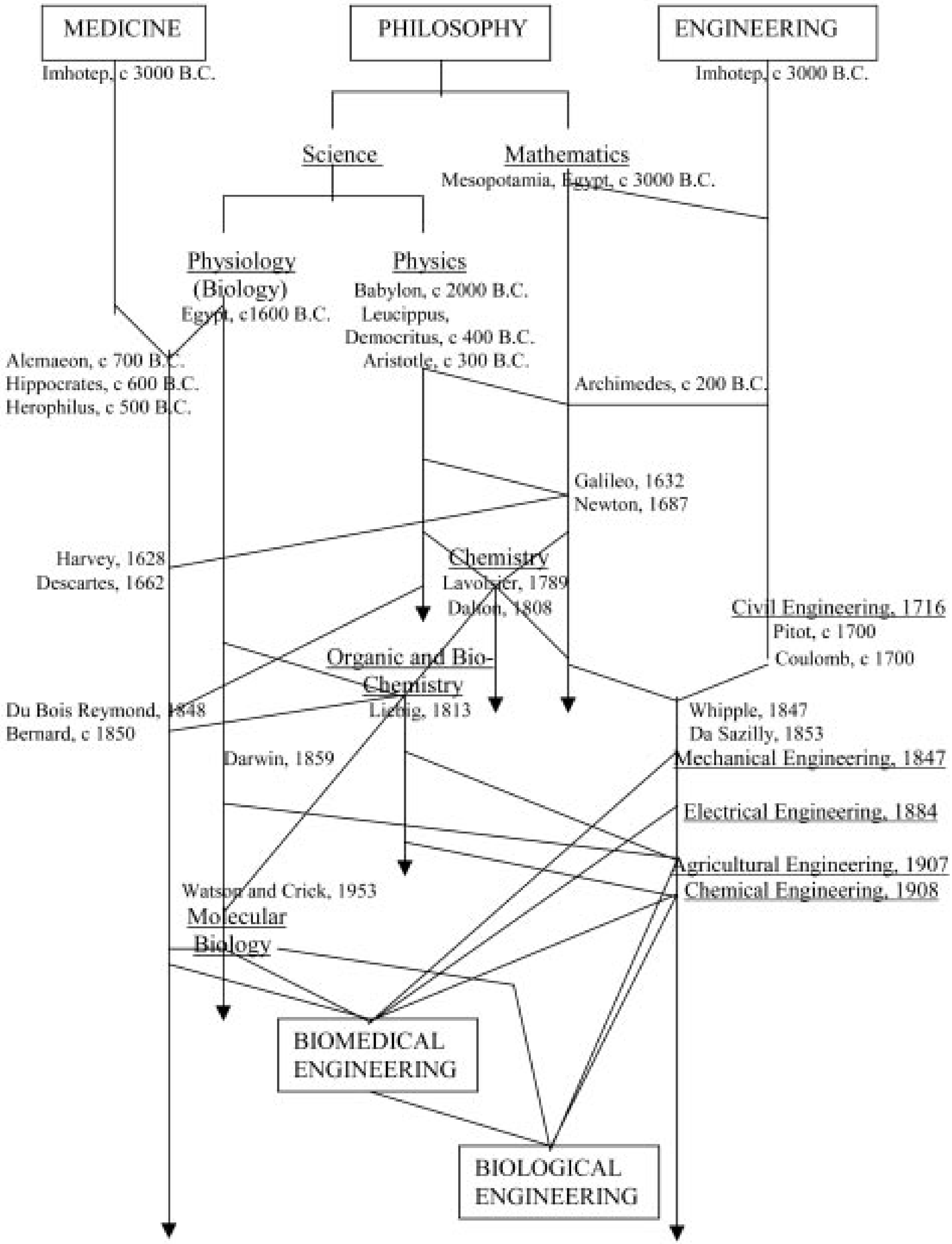

Fig. 1. The genealogy of Biological Engineering.

through the ages toward their modern scientific incarnations necessitated prior, if not contemporaneous, advances in the field of natural philosophy, and specifically in its branches of mathematics and the sciences of physiology (biology) and physics. Existing specimens of mathematics older than the renowned Egyptian papyri, such as the Rhind Papyrus (17th century BC) in the British Museum and the Golenishchev Papyrus (19th century BC) in the Moscow Museum of Fine Arts, are found among the surviving clay tablets of Mesopotamian scribes dating from the Sumerian kingdoms of the 3rd millennium BC and the Babylonian regimes of the 2nd millennium BC [1]. These tablets show that the Babylonians devised a versatile numeral system, developed computational methods and solutions for linear and quadratic problems, and established geometric relations such as that between the hypotenuse and the two legs of a right triangle, now commonly known as the Pythagorean theorem, more than a thousand years before the Greeks used it [1]. There is also evidence that a crude form of surveying and elementary mathematics came into use in Egypt as early as 3000 BC [6]. Pythagoras (530 BC) and Euclid (300 BC) would contribute significantly in advancing the mathematics of classical antiquity [8].

Elemental knowledge of physiology can be traced back to ancient Egyptian papyri pertaining to medical subjects. One contains anatomical descriptions (1600 BC) and another indicates that the importance of the heart had been recognized [1]. Alcmaeon, a Greek philosopher in the 6th century BC, was the first recorded physiologist to have practiced dissection of human bodies for research purposes [1]. He dissected the brain, optic nerves and the eye, and concluded that the 'seat of sensations is the brain' [8]. Herophilus (4th century BC) also dissected human cadavers and advanced anatomy significantly [1]. Alcmaeon, Herophilus and also Hippocrates, a Greek physician in the 5th century BC who emphasized the effects of food, occupation and especially climate in causing disease [1], helped bridge physiology into the practice of medicine.

Physics had its early beginnings in the field of astronomy. As early as 1800 BC, Babylonian astronomers worked toward the accurate prediction of astronomical phenomena, especially the first appearance of the new moon [1]. Their work represented one of the earliest systematic, scientific treatments of the physical world. A notable milestone in the development of the physics of classical antiquity occurred, however, when Leucippus (430 BC) and later his pupil Democritus (420 BC), theorizing on the nature of matter, advanced the philosophy of atomism [8]. They posited that matter is composed of 'an infinite number of [atoms] and they are invisible owing to the smallness of their bulk. They move in the void and by their coming together they effect coming into being, and by their separation passing away' [9]. This early, if rudimentary, *mechanistic* view of matter, however, clashed violently with the philosophy of one of antiquity's most prominent and influential figures, Aristotle [8]. Aristotle attacked the atomic theory of matter, declaring that, 'There are some who make chance the cause of both these heavens and of all the worlds' [9]. Aristotle's first central dogma was that 'Nature does nothing in vain' [9]. To him, things do not happen at random—as in the random coming together and separation of atoms—but always with an end in view. And this end, to Aristotle, is the final cause, the reason for things happening [8]. Couching his argument in terms of his concepts of 'potentiality' and 'actuality', Aristotle explained that 'Actuality is to potency as that which is building is to that which is capable of being built . . . and that which has been shaped out of matter to matter' [9]. Aristotle concluded that things develop toward an end. Thus, the embryo chick in its egg is potentially a rooster, a block of stone is potentially a statue, etc. His concept was thoroughly *teleological* (i.e. the end governs the means) [8]. As such, he could conclude that 'the man is prior to the boy and the human being to the seed; for the one already has its form and the other has not, and because everything that comes to be moves towards a principle, i.e. an end (for that for the sake of which a thing is, is its principle, and the becoming is for the sake of the end), and the actuality is the end, and it is for the sake of this that the potency is acquired' [9].

Aristotle's second central dogma was that 'All substance appears to signify that which is individual' [9]. Describing 'individual' as 'the individual man or horse,' Aristotle defines substance (the individual) to be irreducible [8]. Thus, Aristotle could not understand how the random movement of 'billiard-ball' atoms could account for the biological phenomena he had directly observed—namely, the ordered sequential processes of embryology, the structure and function of animals, the similarity of parent and offspring, etc. [8].

Since Aristotle, as those of his predecessors like Plato, aspired to a philosophy that constituted a comprehensive world system [8], he applied his dogmas both to physics and biology. Consistent with his theories he applied to biology, Aristotle described motion, which he considered to be the datum with which physicists were concerned above all else, also in terms of potentiality and actuality. A body in motion is first potentially and then actually at the finishing line [8]. Thus, from the 4th century BC, both biology and physics fell captive to the battling philosophies of Democritean Mechanism and Aristotelian Teleology. For mechanism, the means governs the end. Mechanism posits that a given response by a living or a non-living entity is the necessary result of sequence of causes originating from the entity's physical structure and chemical constitution [10, 11]. For teleology, mechanism's antithesis, the end governs the means. Teleology (Gk. *teleologia*: *telos*, *teleos*, an end + *logia*, doctrine, science or theory) [12] postulates that a given response by a living or a non-living entity is drawn out of or elicited from the entity by an end, a goal or a purpose. Some definitions of teleology imply that a teleological entity possesses intrinsic purposiveness—that is, the entity 'desires some goal, and is behaving in a manner it believes appropriate to the attainment of it' [13]. While teleology has been historically associated with vitalism, or the doctrine of vital (spiritual) forces, its modern definition eschews those connotations [14, 10].

Owing to Aristotle's coherent theories and his vast influence, achieved in part through the school that he founded in Athens, the Lyceum, his teleological biology and physics (which included his false analysis of motion requiring that 'everything that is in motion must be moved by something' [9]) gained widespread acceptance until the 16th century [8]. Their more subtle forms, mixed with the vitalistic or mystical concepts of spirit and essences, however, would continue to linger and would not be completely extirpated from the natural sciences until the end of the 19th century.

OUT OF QUANDARY: THE ASCENT OF MECHANISM

There was a brief shining moment in classical antiquity, even during the powerful reign of Aristotelian physics, when mathematics, science and engineering blended together harmoniously and even in a very modern way. Archimedes (287–212 BC), a protégé of King Hieron of Syracuse (*c*. 270–215 BC), laid the theoretical foundations for hydrostatics and mechanics through his application of mathematics in the treatment of physical phenomena. Indeed, his mechanistic achievement helped him design ships, foremost of which was a 400-foot-long combination warship, merchant and pleasure vessel, which eventually was given to the ruler of Egypt, Ptolemy Philadephos (285–246 BC) [7]. What the work of Archimedes underscored, though perhaps not publicly evident at the time, was that his reliance on mathematics obviated any need for him to appeal to an Aristotelian final cause.

Approximately 18 centuries later, Galileo Galilei adopted the same mathematical approach that Archimedes employed, insisting that 'the book [of nature] cannot be understood unless one first learns to comprehend the language and read the letters of which it is composed. It is written in the language of mathematics and its characters are triangles, circles and other geometrical figures, without which it is humanly impossible to understand a single word of it; without these one wanders in a labyrinth' [15]. Galileo was firm in believing that only the application of mathematics could provide an escape from the quandary of scholastic arguments [8]. Without appealing to a final cause and ignoring the vitalistic concepts of spirit and essences, he treated external bodies only in terms of 'sizes, shapes, numbers and slow or swift motion.' This was revolutionary in the 17th century, since it succeeded in starting to divest science of teleology and of the then conventional scholastic concern with the subjective notions of spirit and essences, and since Galileo's decidedly mathematical philosophy contrasted starkly with the qualitative Aristotelian orthodoxy [8]. Indeed his mathematical approach enabled Galileo to take on Aristotle's physics of motion, culminating in Isaac Newton establishing one of the laws of the new physics, providing that 'Everything proceeds at rest or in rectilinear motion unless acted upon by a force' [9]. Newton's first law finally delivered the *coup de grace* to Aristotle's spurious formulation that 'Everything that is in motion must be moved by something.'

After Galileo and before Newton there was the Roman Catholic priest Pierre Gassendi, who in 1649 revisited and revived the atomism of Leucippus and Democritus. To make the theory, which had long been branded atheistic, acceptable to the Roman church, he asserted that atoms were in the beginning made by God and that they were endowed with a certain impetus by which they are compelled to move until the end of time [8]. Indeed, it was quite probable that Gassendi's revival of atomism influenced Newton's assumption of material bodies being composed of particles or corpuscles. Thus, it was the triumvirate of Galileo, Newton and Gassendi that promptly provided a clear path for the physics of the 17th century to escape the clutches of the moribund Aristotelian teleology and to follow the lead of a reinvigorated mechanism.

For biology, the escape from teleology toward mechanism was provided also during the 17th century by the landmark works of Paul Harvey and René Descartes. Harvey, through his elegant and extensive experimentations, described for the first time in his 1628 publication, *On the Motion of the Heart and Blood*, the hydraulic understanding of the cardiovascular system, confirming that the heart is a muscle, that its most important function is to pump blood into blood vessels, and that blood actually circulates within the body [11]. The mechanistic model by Harvey, who today is accorded the honor of being the founder of modern physiology, would later help falsify the long-held vitalistic concept that food was converted into blood in the liver and that some of the blood was carried to the heart to receive a quantity of vital spirit [11].

In the 1630s, following Harvey's important work, Descartes formulated a thoroughly mechanistic conception for the biological system [8]. Owing to his dichotomous metaphysical belief that 'the soul . . . is entirely distinct from the body,' he postulated that the activities of the body could be treated solely as the activities of a piece of intricate machinery, necessitating no need of any concept (teleology, vitalism) which could not be equally well applied to the process of non-living entities [8]. Such a mechanistic approach guided Descartes methodically in his various investigations, leading to his numerous contributions in the physiology of the nervous system and the physiology of motion, among other fields. And though the actual theories of Descartes concerning animal movement were soon discarded, his mechanistic approach continued to endure, bestowing on him the honor of having 'opened up a road to the mechanical theory of these processes, which has been followed by all his successors' [16]. In the field of neurophysiology, 'the modern view has in principle departed but little from the lead that Descartes gave it' [17]. Descartes was expressly followed by those who came after him in the second half of the 17th century, including William Croone and the mathematician and physicist Giovanni Borelli, both of whom studied muscular contractions mechanistically, considering the body exclusively as 'a kind of machine or automaton' [8]. Croone's and Borelli's *iatrophysics* or *iatromechanics* further advanced the influence of mechanism in biology [8].

One more advance, however, was necessary to enable the dominance of mechanistic philosophy in both physics and biology to transpire: the development of the science of the inorganics, chemistry. Starting with Robert Boyle, who in 1660 attributed the 'spring' or compressibility of the air to his philosophy that 'the air is nothing but a congeries or heap of small and (for the most part) of flexible particles. . . ' to Priestly's discovering oxygen in 1774, and on to Lavoiser's quantitative experiments in 1789 showing that oxygen is consumed during animal respiration and is substituted by carbon dioxide in the respired air, the new science of chemistry was inaugurated and began to be revolutionized [8]. And using his own conceptual models of atoms at the beginning of the 19th century, John Dalton successfully accounted for the characteristics of gas solubility, which had been described earlier by Henry (now known as Henry's Law) in terms of their constituent atoms [8]. Dalton also showed that the partial pressures of gases could be attributed to their atomic constituents. And, more importantly, Dalton realized that the observations made earlier by other chemists, which came to be known as the law of multiple proportions, could be explained if it was supposed that the chemical elements were in fact atomic in nature and that combinations were produced by atomic combinations [8]. Dalton published his major work, *A New System of Chemical Philosophy*, in 1808, and the completed foundations of mechanistic philosophy for the natural sciences were subsequently irrevocably established.

A far-reaching consequence of the works on motion by Galileo in 1632 and by Newton in 1687 and of the establishment of chemistry at the dawn of the 19th century was that scientists began to understand that they could fully account for and explain physical phenomena without appealing to an Aristotelian final cause or its associated concept of vitalism. An efficient or prior (or mechanistic) cause was all that was necessary. This realization later prompted Helmholtz to acknowledge that 'the task of physical science is finally to reduce all the phenomena of nature to forces of attraction and repulsion, the intensity of which is dependent upon the mutual distance of material bodies . . .' [18].

REINVENTING MEDICINE AND ENGINEERING: THE TRIUMPH OF MECHANISM

As the winds of mechanism blew over the domains of the physical sciences in the 19th century, it was perhaps inevitable that they were also carried over into the biological realm. With the establishment of chemistry, the propitious time for the full implementation of the mechanistic program that Descartes envisioned for biology in the 17th century finally arrived. The publication of *Animal Chemistry* by Justus Liebig in 1813 commenced the crossover of mechanistic chemistry into the provinces of physiology and medicine. In the process, Liebig ushered in the science of organic chemistry, the harbinger of today's biochemistry and molecular biology [8]. Employing his meticulous and quantitative analytical chemistry, Liebig established the chemical composition of the foods consumed by animals and the constituents of many animal tissues, body fluids and excretory materials [19]. His extensive data led him to the conclusion that, 'In the animal body, the food is the fuel; with a proper supply of oxygen we obtain the heat given out during its oxidation or combustion' [19]. Thus, realizing that the body constitutes a form of biochemical machinery, Liebig finally explored successfully what for a long time had been *terra incognita* to mechanistic explications—the source of animal heat [8]. His data confirmed that 'the mutual action between the elements of the food and the oxygen conveyed by the circulation of the blood to every part of the animal body is the source of animal heat' [19].

Other physiological processes, including neurophysiology and animal homeostasis, which remained shrouded in mystery for ages and which earlier necessitated the invocation of teleology or vitalism, eventually yielded to completely mechanistic explanations [8]. The early works by Galvani (*c.* 1791), Volta (*c.* 1792) and Metteuci (*c.* 1840), linking electromagnetism and neurophysiology, culminated with Du Bois Reymond establishing in 1848 the physical (mechanistic) basis for the nerve impulse [8]. Helmholtz later successfully showed, in 1850, that frog nerve conducted an impulse at a rate of approximately 30 m/s, confirming Du Bois Reymond's vision of a purely nonteleological (mechanistic) nervous sytem [8]. And Claude Bernard (*c.* 1850) opened the way to the mechanistic understanding of animal thermoregulation, showing that 'the calorific function proper to warm-blooded animals is due to a perfecting of the nervous mechanism, which, by incessant compensation, maintains a practically fixed temperature in the internal environment' [8]. Thus, Bernard correctly identified the cybernetic-control mechanism employed by the nervous system in the regulation of body temperature long before the concept of feedback-control mechanism was fully understood in the 20th century.

And, ultimately, Schwann's cell theory (1839), Darwin's theory of evolution (1859), the perfection of the atomic theory in the 20th century by J. J. Thomson (discovery of electrons, 1897), Rutherford (electrons orbit around nucleus, 1911), Bohr (quantized orbits, 1913), de Broglie (electron waves, 1923) and Schroedinger (wave mechanics, 1926) as well as the discovery of the structure of DNA by Watson and Crick (1953), among others, paved the way for a thoroughly mechanistic approach in deciphering the complex biochemical processes that lead to biological self-assembly (or morphopoiesis). And while today's understanding of morphopoiesis remains far from complete, it is nonetheless established that its processes do not appeal to any teleology.

As for engineering, Archimedes emerged easily from the long lines of mostly obscure military and civil engineers from ancient Egypt, Greece, China and Rome as the archetypal engineer-scientist—the harbinger of today's modern engineers who seamlessly combine science and mathematics in engineering design [7]. Centuries had to pass before the rightful successors of Archimedes appeared in a small coterie of scientist-engineers in France at the beginning of the 17th century, the foremost members of which were Pitot (1695–1771), the inventor of the pitot tube, and Charles Coulomb (1736–1806), a pioneer in the study of electricity and magnetism [7]. But although one of the first engineering schools in the world, Ecole Nationale des Ponts et Chaussées (National School of Bridges and Highways), opened in France in 1747, providing engineering with a stronger mathematical and scientific foundation [7], it was not until 1847 that 'the beginning of a truly rational and scientific design in . . . engineering' occurred, marked with the publication of Squire Whipple's first treatise on stresses in trusses [20]. This was followed in 1853 by De Sazilly's analysis of dam design. Since 1847, engineering 'design passed out of the hands of the practical man into the hands of those with scientific training' [20]. From the 19th century to the present, the indispensability of quantitative physical principles to respectable engineering design has become simply axiomatic.

The development of modern engineering both led to and was spurred on by the formation of professional engineering societies. France's Corps de Ponts et Chaussées (Bridge and Highway Corps) was established in 1716, while Great Britain's Society of Civil Engineers was founded by John Smeaton, the first man to call himself a civil engineer, in 1771 [7]. After this society's dissolution in 1792, some young British engineers formed the Institution of Civil Engineers in 1818 [7]. And as the Industrial Revolution in Great Britain transpired in the 19th century, providing impetus to the development of machinery of all types, mechanical engineers came to be recognized and founded the Institution of Mechanical Engineers in Birmingham, England, in 1847 [1]. Meanwhile, electrical engineering, which emerged in 1864 when the Scottish physicist James Maxwell summarized the basic laws of electricity in mathematical form, became in demand with the rise in the practical applications of electricity, including Alexander Graham Bell's telephone in 1876, Thomas Edison's incandescent lamp in 1878 and the latter's first central generating plant in New York city in 1882 [1]. The American Institute of Electrical Engineers was founded in 1884 [21].

The collision course between modern engineering and biology began with the ushering of the Industrial Revolution into the agricultural farms beginning in the latter part of the 19th century, leading to the emergence of modern agricultural engineering [21]. (Agricultural Engineering is as old as the agricultural industry. Its heritage dates from farm implements, structures, and the post-harvest processes invented by ancient civilizations.) The American Society of Agricultural Engineers was founded in 1907 [21], galvanizing the application of engineering to 'the problems of biological production and to the external operations and environment that influence this production' [1]. Indeed, modern Agricultural Engineering in the broadest sense is the first bioengineering discipline. Finally, chemical engineering also materialized toward the end of the 19th century, brought into existence by the demands of the manufacture of chemicals and the development of the petroleum industry, whose novel technical challenges at the time could not be met by the traditional chemist or mechanical engineer [1]. The American Institute of Chemical Engineers was established in 1908 [21].

Thus, around the middle of the 20th century, the mortal combat between mechanism and teleology, which lasted for over two millennia, finally reached its irrevocable dénouement, with mechanism pillaging from the vanquished teleology the latter's treasured possessions—namely, the sciences of physics and biology and the practice of medicine. The stage was set for the melding of engineering and biology to finally occur.

THE RISE OF BIOMEDICAL ENGINEERING

Organized discussions on the founding of the new discipline of biomedical engineering must have taken place as early as 1947, as suggested by the first published Digest (book of abstracts) of the Annual Conference on Engineering in Medicine and Biology held in Chicago, IL, in 1962, which was billed the 15th of such annual conferences. The 15th annual conference was sponsored by the American Institute of Electrical Engineers and by the Instrument Society of America (ISA). For the 17th annual conference held in 1964 in Cleveland, OH, the Joint Committee on Engineering in Medicine and Biology participated as co-sponsor, in addition to the Institute of Electrical and Electronics Engineers (IEEE) and the ISA.

The American Society of Mechanical Engineers (ASME) became a participant in 1965 for the 18th annual conference, and the American Institute of Chemical Engineers (AIChE) became a participant in 1967 for the 20th annual conference. The following year, in 1968, the Biomedical Engineering Society (BMES) was founded. It is noteworthy that the Biological Engineering Society in the United Kingdom was founded in 1960, though their first conference was not held until 1970.

The Alliance for Engineering in Medicine and Biology became the official sponsor of the Annual Conference on Engineering in Medicine and Biology beginning in 1970. That year the Alliance was composed of 18 organizations, including IEEE, ASME, ISA, AIChE and the American Society for Engineering Education (ASEE). For the 1971 conference, the Alliance grew to 21 organizations, which included the American Society of Agricultural Engineers (ASAE). In 1978, ASME's Bioengineering Division, in cooperation with the Heat Transfer Division, held its first conference on Advances in Bioengineering in San Francisco, CA. The following year, in 1979, the Engineering in Medicine and Biology Society (EMBS), a group formed within IEEE, held its first annual conference in Denver, CO. Meanwhile, the Annual Conference on Engineering in Medicine and Biology as sponsored by the Alliance would continue in existence until 1984, when it published its last proceedings for the 37th annual conference.

Marquette University in Milwaukee, WI, was probably the first academic institution to have established a program in Biomedical Engineering, dating back to 1953 [22]. A survey conducted and published by the *Medical Electronics News* in 1966 showed that as many as 37 American academic institutions offered programs in Biomedical Engineering at various levels [23]. By the end of the 1970s, Biomedical Engineering had become an established academic discipline and profession.

THE EMERGENCE OF BIOLOGICAL ENGINEERING

Even as Biomedical Engineering was coalescing into a defined discipline in the 1960s, there was some recognition that Biomedical Engineering was in reality a sub-discipline of a larger umbrella discipline, i.e. Bioengineering or Biological Engineering. For instance, the School of Engineering at the University of Santa Clara in Santa Clara, CA, which in 1966 had both undergraduate and graduate programs in Bioengineering, proposed that the term 'Bioengineering' be used in the broad sense, 'including all aspects of engineering and biology as they are integrated to form a single discipline', so that 'Medical Engineering,' 'Medical Electronics,' and 'Biomathematics' then logically denote sub-specialties of 'Bioengineering' [24]. The same sentiment was echoed in the same year by the Case Institute of Technology in Cleveland, OH, which established a clear divide between Bioengineering and Medical Engineering in their programs [25]. Further, defining 'Bioengineering' as 'the application of the knowledge gained by a cross-fertilization of engineering and the biological sciences so that both will be more fully utilized for the benefit of man,' the Engineers Joint Council Committee on Engineering Interactions with Biology and Medicine indicated that Bioengineering is a part of at least six disciplines; namely, 'Medical Engineering, Environment Health Engineering, Agricultural Engineering, Bionics, Fermentation Engineering, and Human Factors Engineering' [26]. Errett Albritton [27] of the National Institutes of Health (NIH) also ascribed a broad domain for Bioengineering research, including 'Biological Systems,' 'Ecological Systems,' 'Prostheses,' 'Transducers,' 'Laboratory Instrumentation,' and 'Bionics.'

The predominant interest in the 1960s and the 1970s, however, remained the establishment of a decidedly Biomedical-Engineering discipline as opposed to the more general field of Biological Engineering. Indeed, even the resolve of the academic institutions mentioned above to keep an explicit distinction between Biomedical Engineering and Bioengineering buckled over time. Today, the Case School of Engineering at Case Western Reserve University only offers Biomedical Engineering, while the School of Engineering at the University of Santa Clara offers neither one.

Meanwhile, at around the same time that enthusiasm for Biomedical Engineering was rising in the 1940s, interest in the application of engineering principles to fermentation processes—a significant impetus to the conception of a broader biological engineering—was also mounting [28]. The American Chemical Society (ACS) established its Fermentation Section in 1947. The section was later granted a permanent division status within ACS in 1963, with its name changed to the Division of Microbial Chemistry and Technology. (The division's name was changed in 1976 to Microbial and Biochemical Technology Division, and again in 1989 to Biochemical Technology Division [28].) In 1966, the American Institute of Chemical Engineers chartered its Food, Pharmaceutical & Bioengineering Division in support of its interests in both fermentation-related engineering and biomedical engineering [29].

And while IEEE and ASME, among other professional organizations, were endeavoring in the 1960s to establish the Biomedical Engineering discipline, or perhaps a discipline that was Biomedical Engineering with some Biological Engineering included, a small group within the American Society of Agricultural Engineers was also at work attempting to advance a more broad-based discipline of Biological Engineering. This group helped form a Bioengineering Committee within ASAE in 1966 [21]. Also around this time, the Agricultural Engineering Department at North Carolina State

University modified its name to 'Biological and Agricultural Engineering Department', to reflect its interest in biological engineering [21]. Sibling departments at Mississippi State University and Rutgers University followed suit not long after [21].

Although discussions within ASAE in regard to biological engineering surfaced as early as 1937 [21], no significant official actions were taken by ASAE to facilitate the establishment of the discipline within its confines over the next five decades. The late 1980s, however, saw numerous Agricultural Engineering departments in the United States individually reworking their curricula and programs toward the broader Biological Engineering discipline, and including the term 'Biological Engineering' or variations thereof in their department names and/or academic programs. ASAE's first official action on the matter came in 1993, when it formally revised its name from 'The American Society of Agricultural Engineers (ASAE)' to 'ASAE: The Society for the Engineering of Agricultural, Food and Biological Systems.' By 1995, as many as 30 out of 49 Agricultural Engineering academic departments had included 'Biological Engineering' or variations thereof in their department names [30]. Also in 1995, the Institute of Biological Engineering was formally established within ASAE. Five years later, in 2000, IBE amicably gained independence from ASAE, and a Biological Engineering Division was officially formed within ASAE. Today, IBE is the engineering society that represents exclusively biological engineering in its broadest sense. Meanwhile, ASAE, two years before its centennial celebration, officially revised its name in 2005 to 'American Society of Agricultural and Biological Engineers (ASABE)'.

EPILOGUE

The descent of biological engineering betrays the following insights into this still fledgling discipline. First, clearly descending from the intersections of thoroughgoing mechanistic disciplines, biological engineering is also in itself a clearly thoroughgoing mechanistic discipline, not at all teleological. Hence, biological engineering treats biological systems, to which it employs the engineering design process, as exclusively mechanistic systems. As such, biological engineering, just like all other engineering disciplines, borrows and relies on the fundamental laws of physics and chemistry in treating biological systems in a predictive and explanatory manner, and does not possess its own fundamental laws which are unique from those of physics and chemistry nor from those which the other engineering disciplines employ. In short, mechanism breeds provincialism—the philosophy postulating that biology (or the biological system) is a province of the physicochemical sciences and that the advancement of biology hinges upon its application of the methods of the physicochemical sciences [11]. The purpose of provincialism is to secure for biological systems a 'foundation of certainty,' as invoked by Francis Crick, who asserted that 'the ultimate aim of the modern movement in biology is in fact to explain all biology in terms of physics and chemistry. There is very good reason for this. Since the chemistry and the relevant parts of physics . . . together with our empirical knowledge of chemistry, appears to provide us with a "foundation of certainty" on which to build biology. In just the same way Newtonian mechanics . . . provides foundation for, say, mechanical engineering' [31]. The same idea was earlier expressed by Smart [32], articulating that 'If it is asked whether biology can be made an exact science the answer is "No more and no less" than technology. If by "exact science" is meant one with strict laws and unitary theories of its own, then the search for an exact [biological system] science is a wild-goose chase. We do not have laws and theories of electronics and chemical engineering, and engineers do not worry about this lack. They see that their subjects get scientific exactness from the application of the sciences of physics and chemistry . . . There are no laws of biology [or biological system] for the same reason that there are no special "laws of engineering".'

Second, the mechanistic (and also provincialistic) philosophy of biological engineering enables the basic technical activity of Biological Engineering, engineering design, to be successfully accomplished. Since the accomplishment of the engineering design process requires the forging of *explanatory* (functional) and *predictive* (quantitative) relationships among relevant design variables, it follows that the successful accomplishment of the basic technical activity of biological engineering hinges upon the establishment of such explanatory and predictive relationships among relevant design variables in biological systems [4, 5]. (It is noteworthy that, in failing to establish relationships in biological systems that are at least predictive, if not also explanatory, then there would potentially be no authentic engineering design and there would potentially be no authentic biological engineering, at least in the modern sense of engineering [4, 5].) The mechanistic (and also provincialistic) philosophy of biological engineering 'unlocks' or points directly to specific technical principles and tools that can be used to forge relationships in biological systems that are at least predictive, if not also explanatory, enabling the successful accomplishment of the basic technical activity of biological engineering [4, 5].

And third, based on historical evolution, Biomedical Engineering precedes Biological Engineering. Based on disciplinary hierarchy, however, Biomedical Engineering falls under the rubric of the broader, more inclusive, Biological Engineering.

Thus, at the beginning of the 21st century, Biomedical Engineering has emerged as established, both as a defined discipline and as a differentiated profession. Attaining to such an established state is perhaps the most pressing challenge that now faces Biological Engineering as it strives to grow and flourish in the new century and into the future.

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