

Comparisons of ‘Bio’-type Engineering Undergraduate Curricula from Agricultural, Medical and Chemical Origins*

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Since 1965, undergraduate ‘bio’-type engineering curricula have evolved from two primary application origins: agricultural and medical. A third origin emerged around 1999 from the chemical engineering community. Comparisons were made among these three curricula by using 20 selected topics representing life sciences, core and advanced engineering, and mathematics and statistics. Of the life science topics, agricultural and chemical curricula have comparable requirements for organic chemistry and biochemistry that are greater than those for the medical curricula, while agricultural and medical curricula place greater emphases than chemical on introductory biology. Medical curricula dominated requirements for physiology (mammalian), agricultural curricula dominated requirements for microbiology, and chemical curricula dominated requirements for advanced biology topics. Agricultural curricula place a more encompassing emphasis on core engineering topics (engineering graphics, statics, dynamics, fluids, and thermodynamics) than either medical or chemical curricula. With advanced engineering topics, all three curricula have placed greater emphasis on evolving transport phenomena to overcome limitations for biological systems inherent in classical heat and mass transfer. Instrumentation is emphasized strongly in agricultural and medical curricula but not in chemical curricula. Agricultural and medical curricula place comparable and much stronger emphasis on statistics than chemical curricula. Opportunity exists for all three ‘bio’-type curricula to work together to develop a biological engineering experience that appropriately balances broad-based core competencies with specializations for the undergraduate level.

Keywords: agricultural engineering; biological engineering; medical engineering

INTRODUCTION

INTEGRATION of biology and engineering has become an intense process in academia in recent times, yet the origin of this trend in higher education can be traced to as early as the first quarter of the 20th century. Characteristically, this academic integration has focused on agricultural, medical, food, bioprocessing, environmental, natural resources, pharmaceutical, forestry, aquacultural, and ecological engineering applications. Undergraduate engineering curricula have evolved predominantly through agricultural and medical engineering origins, although considerable activity has started within the chemical engineering community since 1999. Consequently, the aim of this article is to compare the characterizing core topics in programs among the agricultural, medical, and chemical engineering communities to understand similarities and differences.

PATHS TO WHERE WE ARE TODAY

Undergraduate curricula designed to apply engineering to living systems were formalized as early as 1905 for specific application to production agriculture [1]. Formation of these programs evolved via routes emanating from both traditional agricultural disciplines like agronomy and from engineering disciplines such as mechanical engineering. Early innovators were envisioning ‘bringing engineering to life.’ These agricultural engineering programs were predominantly in Land Grant institutions in the United States and in similar international institutions. By the late 1940s the number of undergraduate programs had reached a relatively stable level of approximately 50. Beginning in the 1960s, some of these programs started recognizing a broader need to solve engineering problems for biological systems beyond the farm gate. Value-added processing to agricultural raw products in the food chain, human ergonomics and health in the workplace, preservation and use of natural resources, and environmental impacts on biological materials and systems became challenges that also required

* Accepted 16 September 2005.

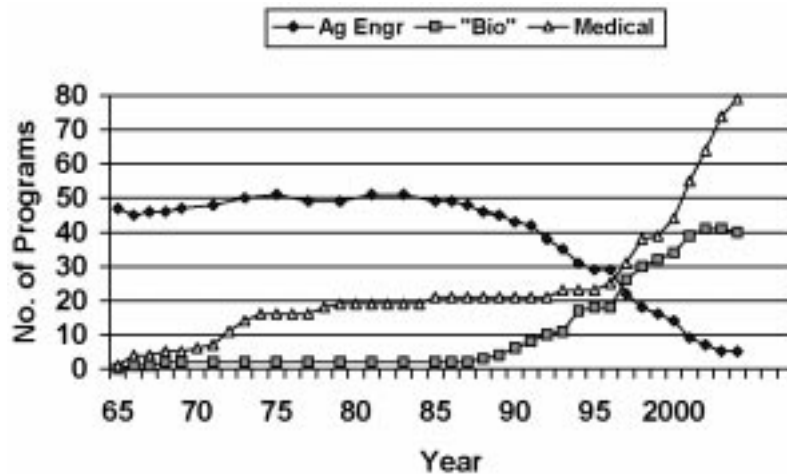


Fig. 1. Chronological numbers of undergraduate programs in biomedical engineering, agricultural engineering, and 'bio'-type engineering (from agricultural origin). Data from the Whitaker Foundation [2] and ASAE.

the expertise of engineering directed to living systems.

In recognition of the broader application of engineering to biology, North Carolina State University changed its curriculum name to *Biological and Agricultural Engineering* in 1966. Mississippi State University created a *Biological Engineering* curriculum in 1968 to add to its *Agricultural Engineering* curriculum. Peer institutions evolved gradually and similarly during the 1970s and 1980s, yet without name alterations beyond Agricultural Engineering. Economic stresses on US agriculture in the mid-to-late 1980s led to a decline of agriculturally based engineering programs to around the upper 40s. In the mid-1980s, however, both job placements of graduates beyond production-agriculture-related industries and an influx of more urban students stimulated a metamorphosis of curricula reflecting stronger linkages of engineering to the biological sciences. In response to these changes, the demographics of students evolved more toward females and toward students with urban backgrounds. Placement opportunities broadened beyond production agriculture toward more value-added processing: food, forestry, biotechnology scale-up, natural resources development, environmental remediation, pharmaceuticals, and medical science applications. As can be seen in Fig. 1, academic programs of traditional agricultural origin started evolving substantially toward 'bio'-type engineering programs in the mid-1980s. In 1997, the number of 'bio'-type curricula exceeded the number of agricultural engineering curricula for the first time (26 versus 22). By 2002, 85% of the curricula of agricultural origin had converted to 'bio'-type curricula.

Curricula designed to apply engineering to human health issues started emerging in the 1950s with favorable economic growth and post wartime concerns of atomic radiation on public health [3]. Significant health-related devices in this era included Geiger counters, pacemakers, defibrilla-

tors, X-ray scintiscanners, and heart-lung machines. This emergence of biomedical engineering was significantly intertwined with the emergence of biophysics and medical physics. In this decade the National Institutes of Health (NIH) supported group discussions and training grants relative to teaching biomedical engineering among a limited few universities: Johns Hopkins University, University of Pennsylvania, University of Rochester, and Drexel University. Out of a strongly research background, instructional programs at these institutions began initially at the graduate level, with the University of Pennsylvania doctoral program in 1961 likely being the first [2].

A second wave of biomedical engineering programs and departments surfaced through an important NIH initiative from 1966 to 1973 at 14 additional institutions [4]: Boston University, Case Western Reserve University, Northwestern, Carnegie Mellon, Duke, Rensselaer, Harvard, MIT, Ohio State, University of Texas at Austin, Louisiana Tech, Texas A&M, Milwaukee School of Engineering, and University of Illinois at Chicago. Figure 1 reveals that after this initial burst, the growth of biomedical engineering programs, BS and Ph.D., rose more slowly during the 1970s and 1980s to a level of approximately 20 undergraduate programs. That stable period was profoundly broken, however, in the early 1990s when the Whitaker Foundation [14] initiated large grant programs to help institutions establish more biomedical engineering departments and programs. Between 1992 and 2004, the number of undergraduate biomedical (or bio-engineering) programs nearly quadrupled [5, 6] to a level of 79 in 2004!

Since 1999, interest in the formation of undergraduate curricula with 'bio'-based content has emerged quickly within the chemical engineering community. Starting with roots in bioprocessing applications, some chemical engineering departments have expanded into biotechnology and

biomolecular areas. Interest in the integration of engineering with biology peaked in November 2003 into the formation of the Society for Biological Engineering (SBE) within the AIChE. In 2004 21 of 151 (13.9%) US departments of chemical engineering had adopted department names with 'bio' in the title. Eleven of these institutions (7.3%) offered a degree program (curriculum) with 'bio' in the title. Since these 11 programs are very recent, they are not shown on Fig. 1.

The emergence of undergraduate programs through three different origins—agricultural, medical, and chemical—which are motivated to apply engineering to the biological sciences, poses intriguing questions relative to their respective topical contents. Curricula of agricultural origin began considerably earlier, focused initially on the undergraduate level, participated in the earliest engineering accreditation efforts [7] and matured to a relatively stable number nearly six decades ago. Over the past two decades, these programs have experienced a significant metamorphosis from a single, production-agriculture industry focus to broader applications with biological systems. At the time of this analysis each of the 38 curricula of agricultural engineering origins had at least one 'bio' specialization beyond just agriculture: in fact, most had multiple 'bio' specializations.

In contrast, undergraduate curricula of medical origin began relatively recently in the mid-1960s. They generally evolved from programs initially focused on graduate-level studies and research. Accreditation of medical engineering curricula is limited and is still evolving. These curricula experienced a quadrupling of growth in the past decade under the influence of Whitaker Foundation financial support.

Until very recently, chemical engineering curricula focused primarily on petroleum and plastics applications with only limited emphasis on biochemical engineering applications. A very rapid transition toward biological applications, however, is currently emerging within the chemical engineering community, motivated by instabilities in their petroleum-based support and by strengthening of biological funding within several government agencies and from private entities.

It is the aim of this article to explore and to compare topical contents of undergraduate curricula originating from these three sources. Could it be possible that they may be converging on core content that can be efficiently and effectively shared at the foundational level of the undergraduate experience?

INFORMATION STRATEGY

The strategy utilized to create a database for comparisons between undergraduate curricula with agricultural and medical origins focused on reviewing the course content listed in their

respective curricula in 1997 and in 2002. Pertinent curricula with agricultural engineering origins were identified from the listings on the ASABE website [8].

There were 48 institutions offering engineering curricula with agricultural origins in 1997 and 46 in 2002. Because of inaccessibility of curriculum data from some institutions, curricula were analyzed from 34 institutions in 1997 and 38 in 2002.

Similarly, pertinent curricula with medical engineering origins were identified from records kept by the Whitaker Foundation and found on websites such as [9, 10].

There were 31 undergraduate medical curricula in 1997 and 64 in 2002. With inaccessibility of curriculum data from some institutions and incomplete implementation of some approved programs, curricula were analyzed from 29 medical institutions in 1997 and 43 in 2002.

In 2004, pertinent curricula with chemical engineering origins were identified from records of the AIChE [11].

Curricula were analyzed from 37 of 151 total institutions (24.5%) with chemical engineering programs which offered identifiable 'bio' content either as an option, concentration, certificate, or degree program.

Excluding basic mathematics, chemistry, English, social studies and humanities, introductory engineering, and general education requirements common to most engineering programs, comparisons of curricula were made for 20 selected topics grouped under four categories as follows:

- *Life Sciences*
 - Biology
 - Organic Chemistry
 - Biochemistry
 - Microbiology
 - Physiology
 - Advanced Biology
- *Core Engineering*
 - Engineering Graphics
 - Physics
 - Statics
 - Dynamics
 - Fluids
 - Thermodynamics
 - Electrical Circuits
- *Advanced Engineering*
 - Biochemical Engineering
 - Instrumentation
 - Transport Phenomena
 - Systems Modeling
- *Mathematics/Statistics*
 - Differential Equations
 - Engineering Mathematics
 - Statistics

Course content was identified primarily by semantics utilized in the listings of courses for suggested undergraduate plans of study. The investigation was not able to determine if sub-course length

modules of the selected 20 topics were embedded within other courses with less explicit titles. Less explicit titles, however, were infrequently observed. For each program considered, the 20 selected topics were designated as Required (R), Elective (E), or not included (–).

SEARCHING FOR DISTINCTIONS

With data sets from 1997 and 2002, comparisons are possible both by origin and by time for the agricultural and medical curricula. The primary reason for reviewing curricula at this 5-year interval is to capture a very dynamic period when the number of undergraduate curricula from medical origin more than doubled from 31 to 64. This period also represents the more recent years of a 15–20 year period when curricula of agricultural origin have evolved strongly toward greater 'biological' emphasis. Moreover, a single data set compiled in 2004 is available for curricula with chemical engineering origin.

Information is summarized for curricula in which the selected topics are *required*, Table 1, and for curricula having the topics either *required* or *elective*, Table 2. Numerical entries represent averages for the curricula investigated. Thereby one can assess the sentiments of various curricula for assuring that certain topics are required of all students or that students have the flexibility to take different topics.

Life sciences

In 1997, introductory biology was required more frequently in agricultural-origin curricula than in medical-origin curricula by approximately 20%. With the exception of physiology, the other life

sciences topics were required 31–58% more frequently by agricultural curricula. Medical curricula required physiology (mammalian) about 53% more frequently. Both microbiology and advanced biology (e.g., genetics, molecular biology, recombinant DNA, etc.) courses were not required in the medical curricula. Consequently, agricultural curricula were substantially broader and more intensive than medical curricula in their requirements for basic life science topics.

By 2002, agriculture curricula had reduced their levels of requirements for all of the selected life sciences topics over a range of 5–24%. The largest reductions were in requiring advanced biology topics. Requirements for physiology had been cancelled completely. Meanwhile, medical curricula significantly increased requirements for introductory biology (+13%), physiology (+15%), and advanced biology (+16%). They increased requirements for biochemistry by 3% and decreased requirements for organic chemistry by 11%. Still none of the medical curricula required microbiology. With the exception of introductory biology and physiology, agricultural curricula still required organic chemistry, biochemistry, and microbiology more frequently. Requirements for advanced biology had become essentially equal (~16%) between curricula from both origins. Physiology requirements had evolved exclusively to medical curricula, and microbiology requirements remained exclusive to agricultural curricula.

Compared with the more recent (2002) agricultural and medical curricula, the 2004 'bio'-type chemical engineering curricula required introductory biology 28% and 33% less frequently, respectively, yet advanced biology topics appeared more frequently by nearly 25%. Chemical engineering curricula focused heavily on requiring organic

Table 1. Percent of curricula with 20 selected topics *required*: 1997 and 2002 medical and agricultural engineering, respectively, and 2004 chemical engineering.

Subject Area	Topic	1997		2002		2004
		Agricultural	Medical	Agricultural	Medical	Chemical
Life Sciences	Biology	88.4	67.9	76.3	81.4	48.6
	Organic Chemistry	79.1	48.2	73.7	37.2	94.6
	Biochemistry	51.2	17.9	42.1	20.9	59.5
	Microbiology	58.1	0	47.4	0	27.0
	Physiology	11.6	64.3	0	79.1	5.4
	Advanced Biology	39.5	0	15.8	16.3	40.5
Core Engineering	Engineering Graphics	55.8	28.6	55.3	20.9	13.5
	Physics	100	100	97.4	100	100.0
	Statics	81.4	51.8	92.1	51.2	16.2
	Dynamics	48.8	44.6	68.4	18.6	0
	Fluids	86.0	50	81.6	32.6	54.1
	Thermodynamics	90.7	50	94.7	51.2	91.9
	Electrical Circuits	76.7	82.1	73.7	72.1	29.7
Advanced Engineering	Biochemical Engineering	32.6	12.5	18.4	2.3	56.8
	Instrumentation	72.1	55.4	52.6	67.4	0
	Transport Phenomena	32.6	33.9	39.5	46.5	43.2
	Systems Modeling	27.9	16.1	18.4	9.3	16.2
Math/Statistics	Differential Equations	97.7	98.2	94.7	88.4	86.5
	Engineering Mathematics	9.3	42.9	7.9	14.0	8.1
	Statistics	32.6	42.9	52.6	53.5	18.9

Table 2. Percent of curricula with 20 selected topics *required* or *elective*: 1997 and 2002 medical and agricultural engineering, respectively, and 2004 chemical engineering.

Subject Area	Topic	1997		2002		2004
		Agricultural	Medical	Agricultural	Medical	Chemical
Life Sciences	Biology	97.2	78.2	81.6	83.7	48.6
	Organic Chemistry	85.0	65.4	81.6	74.2	94.6
	Biochemistry	65.9	31.7	63.2	55.8	78.4
	Microbiology	72.8	6.9	86.9	9.3	54.0
	Physiology	32.2	74.6	28.9	88.4	10.8
	Advanced Biology	57.1	10.3	36.9	37.2	54.0
Core Engineering	Engineering Graphics	58.7	28.6	57.9	20.9	13.5
	Physics	100	100	100	100	100
	Statics	84.3	58.7	94.7	60.5	21.6
	Dynamics	51.7	48.0	78.9	37.2	2.7
	Fluids	86.0	56.9	84.2	62.8	56.8
	Thermodynamics	90.7	53.4	97.3	69.8	94.6
	Electrical Circuits	85.5	89.0	76.3	83.7	35.1
	Biochemical Engineering	50.2	12.5	63.1	27.9	64.9
Advanced Engineering	Instrumentation	75.0	58.8	73.7	90.7	0
	Transport Phenomena	32.6	37.3	52.7	72.1	45.9
	Systems Modeling	72.3	19.5	36.8	25.6	16.2
	Differential Equations	97.7	98.2	97.3	88.4	86.5
Math/Statistics	Engineering Mathematics	15.2	53.2	13.2	18.7	10.8
	Statistics	47.3	49.8	57.9	58.2	18.9

chemistry, nearly 21% more frequently than agricultural and 57% more than medical. Similarly, chemical curricula required biochemistry 17% more frequently than agricultural and 38% more than medical. Only slightly over one-fourth of the chemical engineering curricula required microbiology, and very few required physiology.

When considering combined *required* and *elective* conditions in Table 2, agricultural curricula in 1997 still emphasized the life science courses more than medical curricula with the exception of physiology. By 2002, however, the combined expectations for required plus elective were nearly equal for introductory and advanced biology. Between 1997 and 2002, substantially increased elective options (+37%) for organic chemistry in medical curricula reduced the gap between medical and agricultural curricula as compared on the required basis only (Table 1). Considering combined required and elective conditions, physiology was still predominant in the medical curricula, and microbiology was predominant in the agricultural curricula.

With electives, chemical engineering curricula nearly doubled the opportunity to take microbiology and physiology and increased the availability of biochemistry by about 20%. Relative to agricultural and medical curricula, the chemical engineering curricula changed very little, however.

CORE ENGINEERING

Curricula with agricultural origin in 1997 required engineering graphics, statics, fluids, and thermodynamics substantially more frequently than medical curricula by approximately 27%, 30%, 36%, and 40%, respectively. Introductory electrical circuits were required about 5% more

frequently in medical programs. Both programs required physics at the 100% level and dynamics at about the same level (above 40%).

By 2002, the relationships for requirements of core engineering courses had changed very little between the two curricula. Agricultural curricula had increased their requirements for statics by nearly 11% and for dynamics by 20%. Meanwhile the medical curricula reduced their requirements for dynamics by 26%, for fluids by 17%, and for electrical circuits by 10%. Now both curricula required introductory electrical circuits at approximately the same frequency (lower 70% range). One agricultural curriculum had made physics elective, while all medical curricula retained this requirement.

The 2004 chemical engineering curricula generally required engineering graphics, statics, dynamics, and electrical circuits much less frequently than the 2002 agricultural and medical curricula. Their requirement for thermodynamics at 91.9% was comparable to that for agricultural at 94.7%, and for fluids was intermediate between agricultural and medical. Curricula from all three origins required physics at nearly the 100% level. Electives reflected in Table 2 altered the availability of core engineering courses only slightly for chemical engineering curricula.

Combining *required* and *elective* topics in Table 2, agricultural origin curricula reflected only slight increases in frequencies over *required* only in Table 1. The option to take introductory electrical circuits as an elective was greater for agriculture curricula in 1997 than in 2002. By 2002, the options in the medical curricula to take statics, dynamics, fluids, thermodynamics, and electrical circuits as *electives* had increased substantially over elective options in 1997. It would appear that medical curricula were

acknowledging more the merits of these five core engineering topics, but were not yet prepared to make them requirements. It remains to be shown whether this trend will result in greater requirements for core engineering courses in medical curricula in the future. The fact that agricultural curricula require core engineering topics at such higher frequencies than medical curricula probably reflects the long-term participation of agricultural undergraduate curricula in engineering accreditation since the early 1940s. Coming predominantly from backgrounds of graduate-only programs, medical undergraduate curricula have not been influenced as much by undergraduate engineering accreditation. In fact, of the 64 medical undergraduate curricula in 2002, approximately 24 were indicated as accredited by ABET (Accreditation Board of Engineering and Technology). Virtually all of the agricultural origin curricula were accredited.

ADVANCED ENGINEERING

Relative to the four topics representing advanced engineering, agricultural curricula in 1997 required biochemical engineering, instrumentation, and systems modeling more frequently than medical curricula by 20%, 17%, and 12%, respectively. About one-third of both agricultural and medical curricula required transport phenomena, defined to focus beyond classical heat and mass transfer to specific issues of biological transport to include diffusion, Gibb's Free Energy, bioenergetics, etc.

By 2002, agricultural curricula had appreciably reduced their requirements of biochemical engineering, instrumentation, and systems modeling by 14%, 20%, and 9%, respectively. These curricula, however, had increased their frequency of requiring transport phenomena by 9%. Medical curricula over this same 5-year period reduced their frequencies of requiring biochemical engineering by 10% and systems modeling by 7%. Medical curricula, however, increased requirements for instrumentation by 12% and transport phenomena by 13%. Both medical and agricultural curricula enhanced their requirements for transport phenomena between 1997 and 2002, but medical curricula increased their level of requirement by 7% more than agricultural. A closer analysis of instrumentation topics would probably reflect considerably more specialization in medical curricula toward human health devices. Instrumentation in agricultural curricula tends to focus on a broader viewpoint of measuring instruments for biological phenomena.

2004 curricula of chemical engineering origin required transport phenomena at approximately the same level as agricultural and medical curricula. Systems modeling requirements were similar to those for agricultural curricula and greater than for medical. Chemical engineering curricula, unlike the other two origins of 'bio'-type curricula,

virtually did not require instrumentation, yet they required biochemical engineering at 3 and 25 times greater levels than medical and agricultural curricula, respectively.

Considering combined *required* and *elective* topics in Table 2, both agricultural and medical curricula substantially increased their elective options for all four advanced engineering topics between 1997 and 2002. Although agriculture curricula substantially reduced requirements for biochemical engineering, instrumentation, and systems modeling in this 5-year period, they increased the elective options for these topics by 27%, 18%, and 7%, respectively. Medical curricula had also appreciably reduced their requirements for biochemical engineering and systems modeling, yet they increased elective options for these two topics by 26% and 13%, respectively. In addition to increasing substantially their requirements for transport phenomena, both agricultural and medical curricula also increased their elective options for transport phenomena by 13% and 22%, respectively. Similar to agriculture curricula, medical curricula also increased elective options for instrumentation by 20%. Chemical engineering curricula reflected very little change with respect to advanced engineering topics when elective courses were included in addition to required courses.

MATHEMATICS/STATISTICS

Congruent with engineering accreditation, both agricultural and medical curricula in 1997 required mathematics through differential equations at the 98% level. Medical curricula, however, required engineering mathematics (Fourier transforms, Laplace transforms, Bessel functions, etc., excluding linear algebra) 34% more frequently than agricultural curricula, and statistics 10% more frequently.

Five years later in 2002, agricultural curricula retained their requirement for differential equations around the 95% level, and medical curricula reduced this requirement by 10%, down to 88%. Obviously this reduction was not motivated by engineering accreditation criterion which still specified mathematics through differential equations. Agricultural reduced its requirements for engineering mathematics by 1.4%, and medical reduced requirements by 29% (but still retaining a 6% greater frequency of requirement over agricultural curricula). Both agricultural and medical increased their requirements for statistics, 20% and 11%, respectively. In 2002, requirements for statistics were slightly above the 50%-level for both curricula.

The 2004 chemical engineering curricula compared to the 2002 agricultural and medical engineering curricula revealed that chemical curricula required differential equations and engineering mathematics at comparable levels. Relative to statistics, however, chemical curricula requirements

were approximately 34% lower than for either agricultural or medical.

Comparing between Tables 1 and 2 (*required* versus *required* and *elective*), agricultural curricula very slightly reduced both their requirements and their elective options for engineering mathematics between 1997 and 2002. Over this same 5-year period, medical curricula reduced both their requirements (~29%) and their elective options (~5%) for engineering mathematics for a substantial combined reduction of approximately 34%. In addition to having similar requirements for statistics in 2002, curricula from both origins have a 5% additional level of elective options. The elective options for 2004 chemical engineering curricula were zero for differential equations and statistics and ~3% for engineering mathematics.

SUMMARY DISTINCTIONS

In summary, all 'bio' curricula in engineering from agricultural, medical, and chemical origins have attempted to integrate engineering and life sciences, although in similar and different ways. Agricultural and medical curricula have emphasized introductory biology appreciably stronger than chemical curricula, although the agricultural curricula have shown a tendency to reduce their requirements. Chemical curricula have placed greatest emphases in the life sciences on organic chemistry and biochemistry, while the medical curricula emphasis has been predominantly on physiology, particularly human and mammalian physiology. Agricultural curricula have reflected a broader emphasis across the basic life sciences and a noticeably stronger emphasis on microbiology than the other two origins of 'bio'-type engineering curricula. Medical curricula tend to limit their focus on life sciences to the human health perspective. Although it is one of the few stated prerequisites for medical school, organic chemistry is required twice as frequently in agricultural curricula (74%) and nearly three times as frequently in chemical curricula (94.6%) as in medical curricula (37%)! One might surmise that from a *foundational* perspective, both agricultural and chemical curricula are meeting medical school requirements better than the medical curricula. It is also noticeable that both agricultural and chemical curricula place considerably greater emphases on microbiology than medical curricula, yet the medical workplace is strongly jeopardized by microbiological organisms.

Probably because of their traditional breadth of applications, lengthy experiences with undergraduate engineering accreditation, and emphasis on professional registration, agricultural curricula clearly place a more encompassing emphasis on core engineering topics such as engineering graphics, statics, dynamics, fluids, and thermodynamics than either medical or chemical curricula. All three curricula place almost unanimous

emphases on physics (nearly 100%), and both agricultural and medical curricula emphasize introductory electrical circuits much more than chemical curricula. With a phenomenal 106% growth rate over the 5-year period, medical curricula are reflecting a 10–30% level of elective options with all core engineering topics except engineering graphics and physics. Perhaps this is a sign of a trend toward a stronger appreciation for core engineering topics as the medical engineering community shapes its new curricula in anticipation of undergraduate engineering accreditation.

With respect to the selected advanced engineering topics, all three 'bio'-type engineering origins are rapidly evolving the topic of transport phenomena to reflect biological systems more appropriately than does classical heat and mass transfer, which is more applicable for inanimate applications. Both agricultural and medical curricula have shifted in the interval from 1997 to 2002 from requiring biochemical engineering and systems modeling to providing greater elective options for these two topics. Agricultural curricula have decreased requirements for instrumentation more toward elective options, while medical programs have both increased requirements and elective options for instrumentation. Instrumentation is a more generic topic in agricultural curricula than in medical programs, where the emphasis is heavily on human health instruments. Instrumentation as a specific topic is essentially not required in chemical curricula, although instrumentation applications may be imbedded in other courses.

Inclusion of differential equations remains high in all three curricula, although medical curricula have reduced requirements by 10% in over the recent 5-year interval, despite continuing undergraduate engineering accreditation requirements for mathematics through differential equations. All three curricula retain combined *required* and *elective* emphases on engineering mathematics around the 10 to 20% level. Undergraduate statistics requirements have risen substantially in five years to slightly greater than 50% in both agricultural and medical curricula, yet the chemical curricula have a less than 20% requirement.

Where might all these 'bio'-type engineering efforts be leading?

The truly significant question *now* is what should these three distinct origins of 'bio'-type engineering programs share from our respective experiences? One must ask if a core competency is emerging for a *foundational* undergraduate experience to prepare students efficiently and consistently for the broad and expanding employment opportunities to 'bring engineering to life'? Particularly relevant is the issue of *specialization* appropriate for the undergraduate level versus appropriate preparation for the *breadth* of applications and opportunities available to the undergraduate biological engineer. Or in other words,

what is the appropriate broad-based exposure for the undergraduate engineer that will afford the best preparation for specializations that can be gained at higher levels of graduate study, medical school, advanced studies, workplace experiences, etc.?

Both agricultural and medical undergraduate engineering curricula have been focused on integrating engineering with biology-based problems emanating predominantly out of specific industries, i.e., agriculture and health. Their curriculum development efforts, therefore, have essentially been *industry-focused*. This approach has been unlike mechanical, electrical and chemical engineering disciplines whose roots for curriculum development have been more *science-based*. It would appear historically that the general category of 'science-based' curricula have demonstrated greater sustainability and broad-based recognition.

Academic programs from the medical origin have grown primarily out of research and graduate-level programming. Entry into undergraduate curriculum development has recently been greatly stimulated by the financial resources and stated objectives of the Whitaker Foundation [12, 5, 2]. Without the benefit of these particular financial resources, some in the medical engineering community might question if medical applications are not too specialized for the undergraduate level and if there are sufficient job opportunities for medical engineers with a bachelor's degree as a terminal degree [13, 5].

Curriculum development from the agricultural origin has been more evolutionary, having started nearly a century ago for the initial purpose of practical application of science and scientific methods to the agricultural industry [1, 14]. Curricula were designed initially for the undergraduate level, and accreditation was sought with the earliest initiatives to accredit undergraduate engineering curricula [7]. As the discipline matured and considerable success was achieved for production agriculture, many educators began to recognize new applications beyond the farm gate into areas of value-added processing, natural resources development, environmental protection and remediation, worker health and safety, and biotechnology scale-up. These opportunities suggested expanding areas of 'biology-based' applications for engineering [15]. Even as early as the 1960s, some traditional agricultural engineering departments implemented biological and agricultural engineering curricula. With declining enrollments and placements into alternative and new job markets for value-enhanced biological products in food, pharmaceutical, environmental bioremediation, and health areas, a marked metamorphosis transpired during the 1980s and 1990s of agricultural engineering curricula toward biological engineering curricula [16].

'Bio'-type curriculum development from the chemical engineering community has been very recent. It may be motivated by concerns within the chemical engineering discipline of declining jobs in the petroleum and plastics sectors, apparent new economic interests in bioprocessing and biotechnology ventures, and difficult financial circumstances in the chemical engineering professional society AIChE.

In 1991, two workshops were sponsored by USDA Higher Education Challenge Grants to explore 'improvement of competencies of agricultural and related biological engineers' [17]. The product of these workshops was the identification of areas of core curriculum content as follows:

- Biology for Engineers
- Transport Processes in Biological Systems
- Engineering Properties of Biological Materials
- Instrumentation for Biological Systems
- Modeling of Biological Systems.

Subsequently, over the past decade several textbooks have been written to support these core topics. Participants in these workshops, however, were predominantly educators and industry leaders from agricultural origin curricula. One has to ask if similar workshops are not *now* appropriate for a broader group of participants from all of the emerging and seemingly *converging* 'bio'-type undergraduate engineering programs. One can surmise that there likely is a set of biology-based engineering topics that would serve as a fundamental core for curricula from agricultural, medical, and chemical origins and that could possibly emerge as a single biology-based engineering curriculum. Identification of this core could enhance credibility of undergraduate foundational experiences, enable more efficient utilization of undergraduate instructional resources, and afford sufficient commonality for defining adequate accreditation criterion for engineers in the biological arena.

I submit that academia is moving toward a new biology-based undergraduate engineering curriculum freer of specific areas of application dependency (e.g., agriculture, medicine, food, etc.) and analogous to other science-based engineering disciplines such as electrical, mechanical, and chemical engineering. Our various applications and specializations might be more effectively and efficiently served by foundational undergraduate curricula envisioned by the Institute of Biological Engineering [16] as follows:

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

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