Evolving Trends in Chemical Engineering Education

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Introduction

The goal of this article is to examine the evolution of chemical engineering (ChE) education and recent and future trends that have been impacted by shifts in academic research and industry needs. We first provide a brief historical account of the ChE discipline, in which the major paradigms that have emerged successively are unit operations and engineering science. We next discuss the recent impact that bioengineering and nanotechnology have had on the current emerging paradigm of the molecular engineering of products and processes. Finally, given the future needs for addressing sustainability and energy issues, we anticipate that the next paradigm is likely to be one involving the integration of multiscale and systems analysis. We discuss also the impact that the shifts in paradigms have had on the ChE curriculum and the perceived divergence between academia and industry and the importance of maintaining a basic core of knowledge that defines an evolving ChE discipline. Finally, we note the importance of promoting innovation in the curriculum to support the creation of new products and processes and encouraging entrepreneurship among students in ChE.

Development of ChE

To understand where we are currently, it is good to begin at the beginning and review how the ChE discipline got started. Because several detailed accounts of this birth are available,[1–8] we can keep the description brief. In this section, we borrow heavily from a description given recently elsewhere.[8]

The first record of ChE goes back to January 1888, when George E. Davis gave a series of 12 lectures on the subject at the Manchester Technical School in England. The first 4-year undergraduate ChE degree program was established at Massachusetts Institute of Technology (MIT) by the chemistry professor Lewis Mills Norton in 1888. This program was soon followed by programs at the University of Pennsylvania (1892), Tulane (1894), Michigan (1898), and others. Most early ChE curricula originated from chemistry departments, although there are examples of some evolving from mechanical (eg, Colorado, 1904) and electrical (eg, Wisconsin, 1905) engineering departments as well.

Early ChE curricula included a blend of courses taken by chemists and mechanical engineers, with those in industrial and applied chemistry in the third and fourth years being unique to the field. The discipline received its first unifying theme with the development of the concept of unit operations, which is often called the first paradigm of ChE, and it clearly defined ChE as a new discipline that was different from chemistry and mechanical engineering. This idea was attributed to Arthur D. Little in 1915, as noted in his Chemical Engineering Visiting Committee report to the president and corporation of MIT. This concept grew out of the realization that purely physical operations of chemical processing, whether to produce smaller quantities of fine chemicals or larger amounts of heavy chemicals, all depended on certain common principles of physics and chemistry. The first significant textbook, with the title *Principles of Chemical Engineering,* by Walker, Lewis, and McAdams of MIT appeared in 1923.[9] It was an influential textbook, which charted the education, development, and practice of the ChE discipline for decades.

Soon after introduction of unit operations, attention was devoted to the development of procedures for overall material and energy balances in processes, including single or multiple reactions, recycling, and bypassing, and curricula in the 1930s included courses in industrial chemical calculations. Courses in thermodynamics were introduced in the 1940s[10] and included the properties of gases and liquids and applications of both the first and second laws. This decade also saw the development of courses in equipment and process design. Although there were important efforts in Germany, notably by Damköhler,[11] the systematic development of chemical and catalytic reaction engineering principles in

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the English language, with information on reaction rates and catalysis, waited until the appearance in 1947 of *Chemical Process Principles. Part III: Kinetics and Catalysis,* by Hougen and Watson.[12] By the end of the 1950s, most ChE undergraduates took formal courses in reaction engineering, and courses in process control were initiated.

The 1950s also saw a greater emphasis on the use of analysis and applied mathematics in solving ChE problems; this can be traced to three separate events.[8,13] First, it was recognized that individual unit operations involve a combination of the same basic principles in microscopic momentum, heat, and mass transport, each with similar mathematical descriptions. Thus, a study of the individual transport processes as a unified subject, *transport phenomena,* can lead to a greater understanding of chemical processes, and this concept was greatly aided by the appearance of a famous book with the same title authored in 1960 by Bird, Stewart, and Lightfoot.[14] This promoted the development of other important areas, including fluid mechanics,[15] mass transfer,[16] and polymers.[17] Second, applications of sophisticated mathematical techniques were yielding strong results for the design and operation of separation processes and chemical reactors, as exemplified in the works of Amundson.[18] Finally, the general availability of computers, whereby it became possible to conduct numerical simulations of process models to identify optimal design and operation conditions, spurred the application of analytical and numerical techniques and seeded the development of process systems engineering and modern process simulation.[19,20] These efforts have more recently evolved to include modern computational techniques for optimization.[21,22]

Thus, the 1950s and 1960s saw emergence of the so-called engineering science approach in the discipline, which is the second paradigm of ChE. Unlike the unit operations concept, the idea of engineering science was not unique to ChE as other engineering disciplines also began to incorporate similar ideas to solve problems in their domain at about the same time. This approach led to a ChE curriculum, at both the undergraduate and graduate levels, that was a unique blend of chemistry, physics, and mathematics. The chemical engineers (ChEs) educated in this manner could effectively develop, design, and operate complex chemical and refining processes that typically produced commodity chemicals and a variety of products derived from petroleum and other feedstock.

Current Status: Emergence of Biotechnology and Nanotechnology

In the 50 or so years since the 1960s, the ChE discipline has contributed to many significant developments, such as the design of catalysts and catalytic converters for automobiles, which addressed the major societal need of abating air pollution while maintaining good fuel economy. Among the various factors that have changed the ChE discipline itself, however, two have had profound effects. First was the emergence of biotechnology and related industries, including pharmaceuticals, as important employers of ChEs. A reason for this trend was that biology has developed as a molecular-based science, so its connections can now be made more readily to ChE. Thus, the combination of biological concepts with ChE principles, such as reaction engineering, transport processes, separation processes, and process systems engineering, have demonstrated tremendous value. The first applications of biotechnology were in biochemical engineering, particularly fermentation processes.[23] In fact, such applications of industrial fermentation were responsible for large-scale penicillin production, which led to the age of antibiotics and established biotechnology as an independent field.

The emergence of biologically oriented ChE was greatly aided by the involvement of pioneers such as Robert Langer, Jay Bailey, and others. Bailey and Ollis[24] coauthored a widely used textbook in biochemical engineering, which spurred further developments in the field. Langer, Nicholas Peppas, and colleagues have developed many new technologies, including controlled release systems, which can deliver macromolecular drugs for long periods of time, and the field of tissue engineering.[25] In the latter area, biocompatible synthetic polymers provide a scaffold on which new skin, muscle, and entire organs can be grown. With such a substrate in place, the victims of serious accidents or birth defects can more easily grow missing tissue and lead better lives.[26,27] Another major development in biotechnology is metabolic engineering. Showing both by experiments and analysis that the application of recombinant DNA methods developed by biologists starting in the 1970s to restructure metabolic networks can improve the production of biological products by altering pathway distributions and rates, a number of ChE groups, including Bailey, Reuss, Stephanopoulos, and Palsson and coworkers,[28–31] have laid the foundations of this field. This has become a central area for current biochemical engineering efforts, and many impressive developments have occurred.

Nanotechnology is the field dealing with applications of materials at the nanometer-length scale. Materials with such small dimensions often have properties that are strikingly different from bulk materials. The field originated with a well-known lecture by the Nobel-prize–winning physicist Richard Feynman in 1959, titled *There's Plenty of Room at the Bottom (Data Storage),*[32] where he considered the possibility of directly manipulating individual atoms as a powerful form of synthetic chemistry, different from what was used until then. The field has both experimental synthesis and computational directions and has applications in many areas, such as energy conversion and storage and healthcare. There are potential safety issues related to nanomaterials, but the field has attracted the efforts of many scientists and engineers, including ChEs. An important direction in the synthesis of nanomaterials is molecular self-assembly, which is the spontaneous association of molecules under equilibrium conditions into stable, structurally well-defined aggregates. A pioneer of this field is the prolific chemist George Whitesides.[33] He and other ChE colleagues have significantly influenced the development of the nanotechnology field.[34,35] The utilization of nanotechnology in healthcare applications has led to development of bionanotechnology, a current hot area in which ChEs have made enormous contributions.[36]

In recognition of biology as an important science impacting our discipline, starting about 15 years ago, a number of ChE departments changed their names to include some biological term, such as Chemical and Biomolecular Engineering (eg, Cornell, Georgia Tech, Illinois, University of

California-Berkeley, University of Pennsylvania) or Chemical and Biological Engineering (eg, Colorado, Northwestern, Princeton, Wisconsin). Some of the name changes were also motivated by pragmatic reasons because the emergence of separate bioengineering and biomedical engineering have introduced competition for students and resources in some institutions.

As discussed previously, particularly with the incorporation of biotechnology and nanotechnology in the ChE discipline, it may be claimed that the current paradigm of our discipline is molecular engineering, which again is shared with several other engineering and science fields. This framework derives from the fact that along with a molecular-level description of chemical and biological transformations and processes, there is growing feasibility now to also conduct molecular-scale simulations to calculate the thermodynamic, transport, and other properties of fluids and materials.[37,38] These approaches are now being applied with greater frequency and success for the analysis and design of ChE products and processes.

Other Recent Changes in the ChE Landscape: Curricula and Student and Faculty Hiring

A consequence of the emergence of biotechnology and nanotechnology as key new areas of science and engineering has been an increasing emphasis on pure science, away from engineering, in ChE departments. Although ChE has always been a science-based discipline, the current trend toward pure science versus engineering-based science has manifested in a variety of ways, primarily in the curricula and hiring of faculty.

Nowadays, it is common to have one or more required biology-oriented courses in the undergraduate curricula and required or elective courses in molecular engineering, with the latter replacing more traditional materials science courses, where the content was typically the study of classes of materials, including metals, ceramics, and polymers. Simultaneously, there has been a decreased emphasis on ChE fundamentals. This has led to the consolidation of courses as, for instance, in transport phenomena (typically now only one course in fluid mechanics and one in heat and mass transfer), and in thermodynamics (first and second law and phase and chemical equilibria in one single course!). Process control is no longer required at several universities, whereas the teaching of process design has been largely outsourced to adjunct faculty[39] (typically, retired engineers from industry). Some of these changes have been the result of a trend to reduce the number of courses (promoted by deans) and to make space for new courses (eg, biology, biomolecular engineering).

The hiring of faculty has been expanded to include a significant number of nonchemical engineers and to move away from the traditional ChE areas, as discussed in more detail in the Industry/Academia Disconnect section.

As for the employment of ChEs, typically about 70% of ChE graduates obtain employment in the industrial sector. On the basis of recent data, Figure 1 shows the distribution for industries in which they are employed.[40] Thus, among traditional employers, about 43% of graduates find employment in the chemical and energy industries, whereas about 17% go to the biotechnology/pharmaceutical and food/consumer products industries. This trend in employment away from processes and toward products may change with the growing need for energy production to satisfy worldwide demand as less developed countries raise their standards of living as, for example, by the large-scale utilization of coal technologies in China.[41] There is also growth in engineering services, in the design and construction domains, which hires about 14% of ChEs. Another trend is the growing orientation toward products (30% of ChEs), away from the commodity chemicals (45% of ChEs) emphasized in the curriculum; these numbers are in contrast with approximately 15 and 85%, respectively, 25 years ago.

There are also other trends even with traditional ChE employers, where chemical companies are incorporating more life and nanosciences in research and development and manufacturing, companies are becoming more global, and there are more company mergers with inevitable reductions in the work force. Finally, as compared to prior times, one now typically finds ChEs employed by many companies and industry types over their professional careers. In fact, the Chemical Engineering Progress (CEP) survey noted previously reported that 54% of ChEs had two to four employers in their career, whereas an impressive nearly 20% had 5 to 10 employers. This underscores the importance of stressing ChE fundamentals in the curriculum as these are skills that carry over from one company and industry type to another.

Industry/Academia Disconnect

As discussed in the previous sections, ChE research has experienced in the last decade a very significant growth in the areas of biological engineering and nanotechnology. For instance, in the last decade, probably more than 50% of young faculty were hired in these two research areas. This

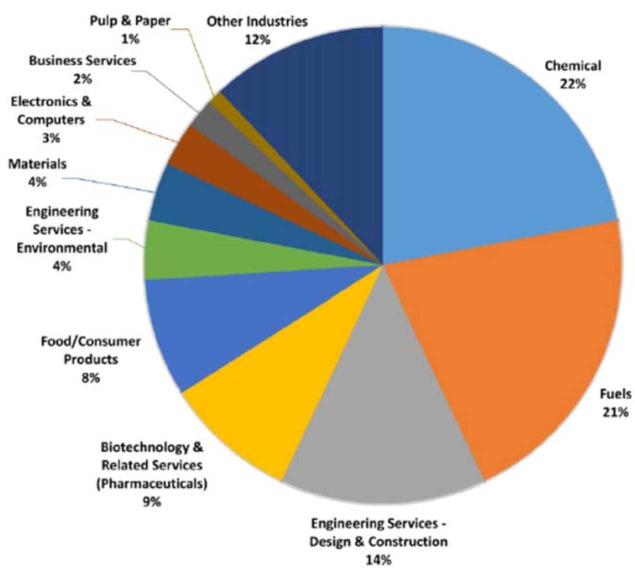

Figure 1. Industrial employment of ChEs (adapted from ref. 40).

Table 1. Revenues of Major US Companies Hiring Chemical Engineers

	2006 ($US billion)	2012 ($US billion)
ExxonMobil	365.5	452.93
Chevron	204.9	241.9
Dow	49.1	53.8
DuPont	27.4	38.72
Procter & Gamble	68.2	82.55
Johnson & Johnson	53.3	67.22
Merck	22.3	48.05
Bristol-Myers Squibb	17.9	21.24
Amgen	13.8	23.6
Genetech	7.6	17.3

Source: Company web sites.

has had the benefit of greatly expanding the scope of ChE and promoting multidisciplinary research, as discussed in the National Research Council report *International Benchmarking of U.S. Chemical Engineering Research Competitiveness*.[41] On the other hand, this new emphasis on biological engineering and nanotechnology, which has been strongly promoted by the funding directions of various government agencies, has caused a significant shift toward pure science and away from core ChE areas. A clear indication of this is the number of young faculty who no longer publish in mainstream ChE journals such as *AIChE Journal, Chemical Engineering Science,* and *Industrial Engineering Chemistry Research*. In fact, for most young faculty, their ultimate goal is to publish articles in journals with high impact factors, such as *Science* and *Nature,* or otherwise in specialized journals. Although publishing in these journals can be regarded as a useful way for ChE research to influence other fields, when taken to the extreme of excluding publication in ChE journals, this can, in the long term, adversely affect the future of the discipline. In fact, this trend has, for instance, already produced a reduction in ChE departments in Japan: there were 24 in 1978 but only 9 in 2012 (S. Hasebe, written communication, January 2014). This was a result of faculty in nanotechnology and biological engineering joining other academic programs at their universities, presumably to obtain access to larger research funds. A similar trend has been observed in The Netherlands, where the Delft University of Technology and the Eindhoven University of Technology are currently the only two departments in the country with *chemical engineering* in their names. Other universities, such as Twente and Groningen, no longer have such departments as organizational units.

A valid question one can raise is whether or not there is an increasing disconnect between academia and industry. If, for instance, one examines the revenues of major US corporations (see Table 1), it is clear that industries that hire ChEs are still largely dominated by petrochemicals, chemicals, consumer products, and pharmaceuticals. Biotechnology firms, such as Amgen and Genentech, have experienced impressive growth, but they are still a small fraction of the entire industry. Furthermore, with recent growth in the energy industry, it is unlikely that biotechnology companies will ever surpass the traditional companies, at least for a few more decades.

The apparent divergence between academia and industry was recognized by the late John Chen, president of AIChE for 2006, who organized an excellent session on this topic at the 2013 AIChE San Francisco meeting. An extensive article on the findings in this session is published by Curtis and Hill.[42] Two interesting pieces of data emerged from this session. On one hand, when industry was polled about the relative importance of six subareas in ChE (see Table 2), it turned out that faculty growth in the different areas was almost opposite. For instance, biological engineering, which was rated as the second lowest area in importance, had seen the most significant increase in faculty size across the three ranks of professor (22%), associate professor (26%), and assistant professor (36%). In contrast, unit operations, regarded by industry as the most important area, saw a significant decrease in faculty size across all ranks, including professor (16%), associate professor (12%), and assistant professor (6%).

In response to the recent trends in academic research toward biological engineering and nanotechnology, a number of companies have expressed concerns about the mismatch with industry, which continues to be largely dominated by the petroleum, petrochemical, and chemical industries. The Dow Chemical Co., one of the largest employers of ChEs, has been the most proactive in this regard by establishing a research funding program over a 10-year period (annually $25 million in the United States and $10 million overseas). Their primary motivation has been to promote research in areas that are relevant for the chemical industry and regarded as key by them.[43,44]

Future Trends in Research

The last decade in ChE research has been largely dominated by bioengineering. This trend has been driven largely by research funding, given the increasing importance of biological engineering for addressing advances in healthcare and in the development of biomass-based fuels and chemicals. The importance of biotechnology is likely to continue as is research in nanotechnology, given the importance of analyzing physical, chemical, and biological phenomena at the atomic and molecular level, with applications in molecular self-assembly for the development of new materials at the nanoscale to control matter at the atomic scale. In the last few years, however, energy and sustainability have emerged as significant challenges that are likely to become new major trends in research and education in ChE. As

Table 2. Ranking by Companies of Relative Importance of Areas[42]

Skill	Average relative importance (from 1 to 5)
Unit operations, transport phenomena, thermodynamics, separation processes	4.6
Reaction engineering, catalysis, kinetics	4.0
Analysis, modeling, simulation, process control	4.0
Materials, surface science, polymers	3.2
Biotechnology, medical and life sciences	2.1
Nanotechnology and its applications	1.8

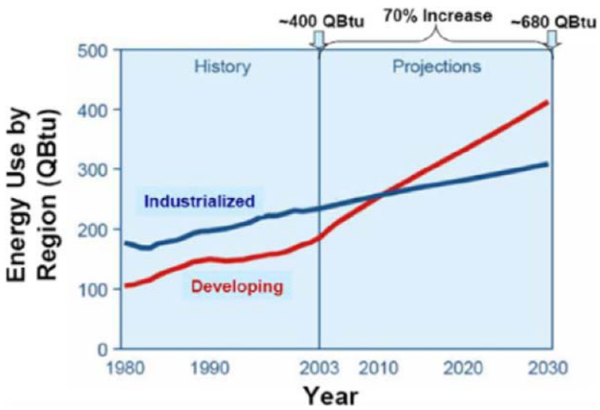

Figure 2. Predicted growth in energy demand.[50]

shown in Figure 2, it is expected that over the next 25 years, there will be an increase of 70% in the worldwide demand for energy. This implies on the one hand, CO_2 levels are increasing to levels not experienced before by mankind (see Figure 3) and, on the other hand, water is becoming scarce to a point that it is estimated by the year 2025 two-thirds of the world population will face water stress (see Figure 4). These trends for energy and sustainability are likely to swing the pendulum back toward engineering fundamentals because of the need to design and redesign sustainable chemical processes that are energy efficient, provide maximum freshwater reuse and recycling, and minimize emissions of toxic chemicals. Furthermore, there will be a need to improve the economics of renewable processes and to minimize the environmental impact of fossil fuels. This will require re-energizing core ChE areas, such as catalysis, reaction engineering, separation, and process design, to accomplish these objectives. A major challenge will be how to make renewable processes for producing fuels and chemicals to be competitive compared to fossil fuels, particularly given the emergence of new fossil sources, such as shale gas, which represents a true game changer in the energy and chemical industry in the United States and other countries, including China, Argentina, and Mexico.[45,46] Regarding this development, because of the cheap availability of methane and C_2 to C_4 natural gas liquids from shale gas, there will be a strong incentive to produce chemicals (eg, ethylene, propylene, and their derivatives and aromatics) with C_1 and light alkane chemistries and conventional cracking.[47–49] In fact, major companies, such as ExxonMobil, Shell, Dow, and BASF, are building new chemical plants using this feedstock at a scale not envisioned even 5 years ago. The cheap availability of natural gas is also leading to its consideration as a transportation fuel for both heavy-duty commercial vehicles and light-duty passenger vehicles. Although this has not occurred in the United States to an appreciable extent yet, compressed natural gas is already a popular fuel choice for transit buses and delivery truck fleets in the Asia Pacific region. Finally, there will also be a greater need to integrate different sources of energy through the application of large-scale supply-chain optimization models.

Roadmap for a Modern ChE Curriculum

On the basis of all of the considerations discussed previously, we can briefly describe the elements of a modern ChE curriculum. In doing this, we firmly believe that the defining characteristics of ChEs, that is, the ability to apply a molecular-level understanding to the conversion of raw materials into more valuable products by physical, chemical, and biological transformations with economic, safe, and sustainable processes, should remain unaltered. Thus, the core subjects in the curriculum, involving mass and energy balances, thermodynamics, transport processes, reaction engineering, separations, laboratories and process design, should continue in the future but with some modifications, as discussed later.

Thanks to their grounding in chemistry, physics, and mathematics, ChEs are employed by an increasingly larger set of industries. On the other hand, in teaching and homework, we use examples primarily from the petroleum refining, petrochemicals, and bulk chemicals industries. It is important to broaden this scope by including examples from other areas, such as materials processing, biotechnology, pharmaceuticals, food processing, particle technology, environment, and sustainability. Similarly, when teaching process design, considerations of energy and sustainability should be included.[53] In addition, exposure to product design[54] should be included in the curriculum to promote innovation in new products, including those in biotechnology and nanotechnology. The previous considerations will require the availability of new textbooks and teaching modules that incorporate these ideas. Most faculty members develop notes from which they teach, in addition to required or supplementary texts and other books, but for wider dissemination, new textbooks are needed. There is, unfortunately, a large gap between having good teaching notes and publishing a finished textbook, complete with worked examples and problems at the end of chapters. Unfortunately, with the pressures of conducting and funding research, most faculty members are unable to find the long-term dedicated effort required for writing meaningful textbooks, but it is a critical activity for our discipline's future.

As noted previously, one or more biology-oriented courses are now required in most ChE curricula. These are often augmented by a number of elective courses, both purely undergraduate and mixed senior-graduate type. With the larger number of new faculty members hired in the biology oriented

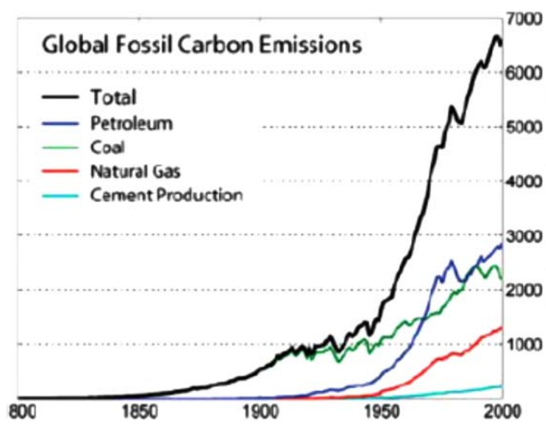

Figure 3. CO_2 emissions over the last thousand years.[51]

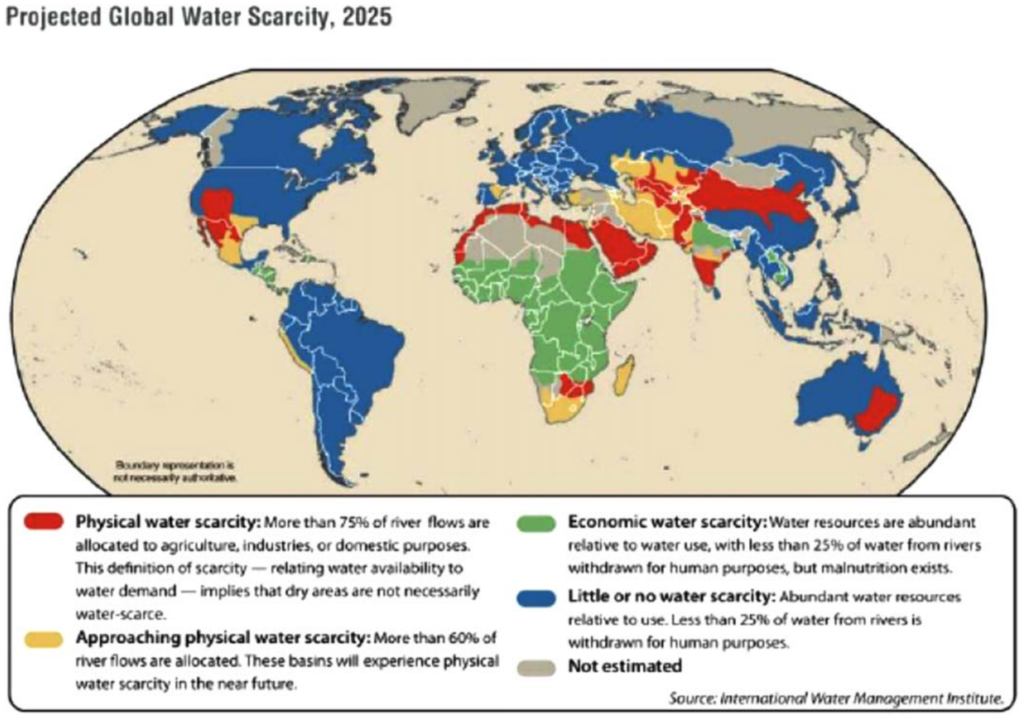

Figure 4. Scarcity of water on worldwide basis.[52]

areas, there is now no shortage of such courses in most departments. There is, however, a shortage of electives that relate to the topics of energy, environment, and sustainability, although some of these topics can be included in the core courses (eg, thermodynamics, reaction engineering, process design). For sustainability topics, a good recent book by ChE authors is available.[55] In addition, whereas safety is now a required part of the curriculum under the Accreditation Board for Engineering and Technology (ABET) requirements, most departments do not have a dedicated course in safety. Fortunately, there is a good book available in this field,[56] but there is a need for more books with newer examples.

Another current trend in most universities involves entrepreneurship, which is a way to spur innovation and lead to companies and commercial products based on university research. This is a way for students and faculty members to conceive an idea, obtain intellectual property, and either start a company by obtaining venture capital or connect with another company that is interested in the idea and agrees to pay some royalty to the institution in exchange for the use of the idea for commercial benefit. Many startup companies have been formed in this manner by faculty members, particularly in the biotechnology and nanotechnology domains, and they are leading to commercial products of value in health care, energy conversion and storage, and other fields. In general, the intellectual property generated by a faculty member is owned by the university, but an attractive financial return to the inventors is typically provided. This trend is promoted strongly at many universities, particularly as they endeavor to generate new sources of income. It should be noted, however, that to be a successful entrepreneur, it is essential to have novel and original ideas that satisfy important unmet needs, for which critical factors are creativity and out-of-the-box thinking; without these, efforts in entrepreneurship will likely not lead to useful outcomes. Although ChE departments typically do not offer courses in entrepreneurship, they are frequently available on campus in other departments (particularly business schools), and many ChE students and faculty take advantage of them. Similarly, there are also courses available in *innovation,* a term used often in the context of creative thought and action.[57]

Teaching methods have also evolved. In addition to the use of traditional classroom teaching, there are numerous opportunities now available for students to take online courses, including so-called massive open online courses. In this context, although there are a number of courses in engineering and other disciplines available via organizations such as edX (https://www.edx.org/), this trend has not taken a strong hold in ChE. Specific practical and educational-theory–related aspects of teaching are available in a book by ChE authors.[58] The important issue of how to teach students to think creatively and critically has also been addressed.[59,60]

As discussed previously, we may claim that the current paradigm of our discipline is molecular engineering. With this, ChEs can design and analyze products and processes by coupling molecular-scale experimental techniques and simulations. As noted earlier, it is also now becoming critical to address future sustainability and energy needs. With the current strengths taken advantage of and upcoming needs accounted for, it appears likely that skills required by future ChEs will involve the simultaneous understanding and incorporation of the principles of molecular engineering, along with multiscale and systems analysis. In fact, a ChE curriculum with this basis has been proposed by the Council for Chemical Research/National Science Foundation (CCR/NSF) Workshops on Frontiers in ChE Education and summarized

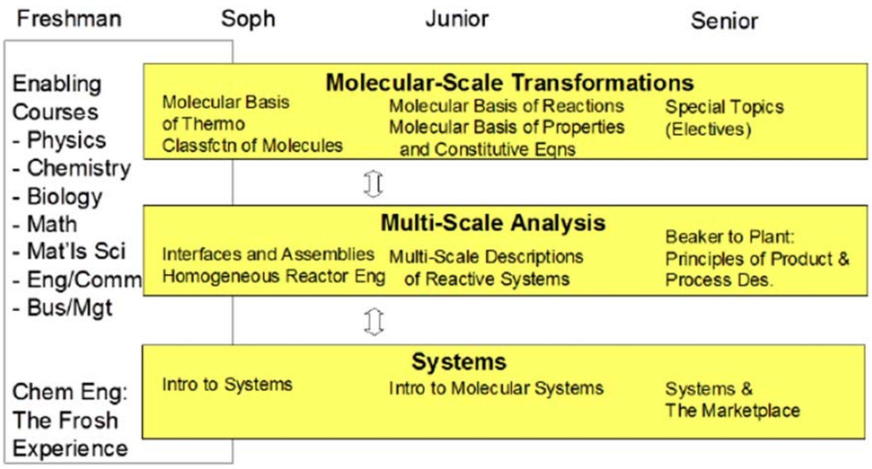

Figure 5. Modern ChE curriculum (Armstrong CEE).[61]

by Armstrong.[61] As noted by Armstrong, an added benefit of the proposed curriculum shown in Figure 5, wherein the molecular level is connected through multiscale analysis to the systems level, is that it reconnects undergraduate education with contemporary ChE research, which has largely been absent for the last several decades. As we assess the current ChE curricula being offered in most universities, however, there is only limited movement in this direction. Recognizing that multiscale issues include both experimental and computational aspects at all lengths and timescales in a product or process, and including molecular engineering principles as well, the emerging next paradigm will likely involve the integration of multiscale and systems analysis.

Concluding Remarks

In summary, ChE education has advanced in numerous impressive ways since the times of George Davis and other pioneers of our profession. Over the intervening century and a quarter since Davis's first lectures, the curriculum has moved progressively from qualitative descriptions to quantitative approaches and today involves principles of molecular engineering along with multiscale and systems analysis. Although ChE has always been a science-based discipline, the current trend toward pure science versus engineering-based science is a potential source of concern in the maintenance of a coherent knowledge base of ChE that is relevant to a significant part of the industry that hires ChEs. Nevertheless, because of the strengths of the curriculum, which include chemistry, mathematics, physics, and biology as underlying sciences, ChEs are finding employment in a wide variety of industries and solve important problems facing society. As long as the curriculum remains challenging and is modernized, with an emphasis on fundamentals and a broader set of examples that cut across different industries, the prospects for a prosperous future are clear and will attract the best and brightest minds to join the ChE profession. This has been a constant feature in maintaining the vitality of our profession, which must continue if we are to have a future even more brilliant than our past.

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