Future Directions in Chemical Engineering Education:

A New Path to Glory

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ConocoPhillips
Lecture Series in Chemical Engineering
given at Oklahoma State University
by Arvind Varma
University of Notre Dame

Stillwater, Oklahoma
April 25, 2003

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FUTURE DIRECTIONS IN CHEMICAL ENGINEERING EDUCATION: A NEW PATH TO GLORY

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The chemical engineering profession is in the midst of great change. Chemical engineers used to focus on making large quantities of small, relatively simple molecules (*commodity* products). Increasingly in the future, they must also make smaller quantities of more complex, possibly biologically active, molecules and nanostructured materials (*specialty* products). Further, we used to only scale things up, now we must also scale down, as in lab-on-a-chip devices and portable fuel cells. In addition, developments in science and other engineering disciplines - such as nanoscale synthesis and characterization techniques, molecular biology and information technology - influence progress in our field. There is a continuing need to consider what will be the energy sources for the future – conventional fuels such as oil, gas and coal, or others such as nuclear, biomass and solar? Finally, growing environmental considerations in society make us aware of the long-term and global implications of our manufacturing practices. I would like to discuss how all these factors, currently at play, will impact the education of chemical engineers primarily at the undergraduate level, although some remarks will also be made towards graduate education and research opportunities.

The Development of Chemical Engineering

Before turning towards the future, it is instructive to examine first how the discipline of chemical engineering evolved. Fascinating detailed accounts of early developments in the curriculum and the profession have been presented in many sources [1-6], so I will keep the discussion here brief.

It is generally agreed that chemical engineering as a distinct discipline began in January 1888, when George E. Davis gave a series of twelve lectures on the subject at the Manchester Technical School in England. He had previously coined the word "chemical engineer" in 1880 and promoted it (unsuccessfully) to found a society of chemical engineers. The first four-year undergraduate chemical engineering degree program was established at MIT by the chemistry professor Lewis Mills Norton in 1888. This program was followed soon by those at the University of Pennsylvania (1892), Tulane (1894), Michigan (1898) and others, including our own at Notre Dame (1909). Most early curricula had their origin in chemistry departments, although there are examples of some evolving from mechanical (e.g. Colorado, 1904) and electrical (e.g. Wisconsin, 1905) engineering departments as well.

The early chemical engineering curricula included an amalgam of courses taken by the 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 development of the concept of "unit operations," which is often called the *first paradigm* of chemical engineering. This concept grew out of the realization that purely physical operations of chemical processing, whether to produce smaller quantities of fine or larger amounts of heavy chemicals, all depended on certain common principles of physics and chemistry. As first noted by Arthur D. Little (1915) in the Chemical Engineering Visiting Committee report to the President and Corporation of MIT, "Any chemical process, on whatever scale conducted, may be resolved into a coordinated series of what may be termed 'unit actions,' as pulverizing, mixing, heating, roasting, absorbing, condensing ... The number of these basic unit operations is not very large and relatively few of them are involved in any particular process." The first significant textbook with the title "Principles of Chemical Engineering," by Walker, Lewis and McAdams of MIT appeared in 1923 [7]. It showed that combining a few principles of momentum, mass and heat transfer, it is possible to understand the unit operations. It was an extremely influential textbook, which charted the education, development and practice of chemical engineering for decades.

Soon after the introduction of unit operations, attention was devoted to developing procedures for overall material and energy balances in processes, including single or multiple reactions, recycle and bypass, and curricula in the 1930s included courses in industrial chemical calculations. Courses in thermodynamics were introduced in the 1940s, which included properties of gases and liquids, and applications of both the first and second laws. This decade also saw development of courses in equipment and process design. Although there were important efforts in German, notably by Damköhler [8], the systematic development of chemical and catalytic reaction engineering principles in the English language, utilizing 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 [9]. By the end of the 1950s, most chemical engineering undergraduates took formal courses in reaction engineering, and courses in process control were initiated.

All through this period, since the early days of the profession, a synergistic relationship existed between academia and industry. Much of university research was supported by industry, and the graduates were readily employed by the growing petroleum refining, petrochemical and chemical industries. The oil companies refined petroleum crude to produce gasoline and

other fuels for the automobiles and airplanes, the petrochemical complexes produced bulk chemicals, while the chemical companies produced these as well as polymers, fertilizers, paints and other specialty chemicals. All these products satisfied a rising demand from society with an increasing standard of living. The growth of the petroleum and chemical industries followed, and in turn catalyzed, developments in chemical engineering.

The 1950s also saw a greater emphasis on the use of analysis and applied mathematics in solving chemical engineering problems, which can be traced to three separate events [10]. First, it was recognized that the 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 [11]. 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 [12]. Finally, the general availability of computers, whereby it became possible to conduct numerical simulations of process models to identify optimal design and operation conditions, also accelerated the application of analytical and numerical techniques. Thus, the 1950s and 60s saw emergence of the so-called *engineering science* approach in the discipline, which is the *second paradigm* in chemical engineering. This approach led to a curriculum, at both the undergraduate and graduate levels, that is a unique blend of chemistry, physics and mathematics. The chemical engineers educated in this manner could effectively develop, design and operate complex chemical processes that typically produced commodity products.

The Current Status and Challenges

In the context of the development of the discipline, we may now examine the current status as it relates to the education and employment of chemical engineers. In doing this, I will be brief, as this topic has been addressed well in the lecture by Ed Cussler last year [13] and elsewhere [14]. Further, much discussion around these issues in the context of undergraduate curriculum revitalization is currently ongoing as a result of the "New Frontiers in ChE Education" workshops organized through the Council for Chemical Research (CCR) and sponsored by the National Science Foundation (NSF). Two NSF/CCR workshops, organized under the leadership of Bob Armstrong of MIT, were held in January and April this year, with a third planned in June [15].

Education

A typical undergraduate chemical engineering curriculum consists of foundation courses in mathematics, physics, chemistry and engineering in the early years, as well as courses in humanities and social sciences that serve to provide a broad education. The chemical engineering courses typically include offerings in mass and energy balances, thermodynamics, transport processes, separations, reaction engineering, process design, process control, and laboratories where principles learned in the lecture courses are reinforced and include elements of both written and oral communications of experimental results and analysis. Finally, there are generally several electives to choose, from chemical engineering as well as other science and engineering disciplines.

A striking fact is that while the discipline of chemical engineering has evolved significantly over the last forty or so years as I shall detail next, the undergraduate curriculum has remained essentially unchanged. The engineering science paradigm continues to dominate the core curriculum as well as the textbooks that are used. The examples utilized in courses continue to

come primarily from the petroleum refining and bulk chemicals production industries.

Employment

Between 50-60% of the B.S. degree chemical engineering graduates in the US seek industrial employment immediately upon graduation, and Figure 1 shows their distribution during the 2000-01 year by nature of the industry. It is remarkable that the skills learned from understanding engineering principles and processes, based largely on physical and chemical transformations, are considered to be valuable by a large number of industries. However, if we consider chemical and energy companies as the traditional employers, then only ~40% chemical engineers find their initial employment there. About an equal number go to the electronic, food/consumer products, biotechnology and materials related industries, which were not significant employers some years ago. Overall, as noted elsewhere [14], only about 25% of the graduates are hired by companies that manufacture commodity chemicals emphasized in the curriculum, while about 50% by those with a product orientation – in contrast with approximately 80% and 15%, respectively twenty-five years ago.

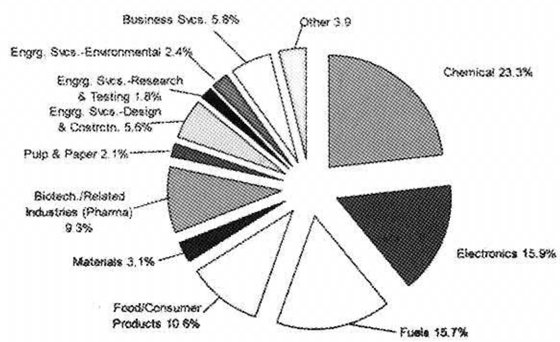

Figure 1. Initial industrial employment of B.S. chemical engineers, 2000-01 year [AIChE, Dept. of Career Services]

In addition to the increasingly wider spectrum of industries where chemical engineers now find employment, several other factors are currently at play even with the traditional energy and chemicals companies:

- The companies are becoming more global, with greater manufacturing and research conducted overseas.
- Many companies are merging into larger ones, with significant reduction of workforce.
- Chemical companies are increasingly incorporating life sciences into their manufacturing and products.
- Chemical engineers cannot expect to work with a single company or industry type and must now accept several job changes over their professional careers.

Other Driving Forces

Some other driving forces are also currently operative and I would like to enumerate some of them, without claiming completeness. First, *biology* is rapidly developing as a molecular based science, so that its connections can now be made more readily to chemical engineering. There are numerous opportunities to couple the molecular level understanding of biological reactions and interactions, with chemical engineering concepts and processes, to result in products of tremendous value. Some examples include bioprocessing for production of pharmaceuticals and even commodity chemicals, metabolic engineering, controlled drug delivery, biomaterials, tissue engineering, functional genomics, gene therapy, drug design and discovery, nano and micro biotechnology for lab-on-a-chip devices, and the list goes on.

Second, there is a current trend towards *establishment of bioengineering and biomedical engineering departments* in universities that has been driven by the Whitaker Foundation grants (see, for example, [16]). Owing to the closest fit, these new programs compete for students and resources that in many instances would otherwise come to chemical engineering.

Third, there is a growing awareness of the pressures that current manufacturing practices place on the environment, in terms of pollutants that require remediation and waste generation that demands disposal and diminishes resource utilization. Thus *environmentally benign processing and sustainable development* is receiving increased attention, both to satisfy environmental regulations as well as to increase profitability.

Fourth, *new educational tools and methods* are being developed that can be utilized to enhance the quality of chemical engineering education. Examples include use of web-based educational materials that can be shared across institutions, web interfaces to run actual laboratory experiments, and simulations to explore influence of parameters or to learn about cases too dangerous to conduct in the laboratory such as explosions.

The Future Directions

Based on the current status, some suggestions can now be made for future directions of chemical engineering education, especially at the undergraduate level. The intent is to provide a framework that takes advantage of the unique aspects in the present curriculum, as well as the changing scene related to employment and developments in other science and engineering disciplines. My basic premise is that the defining characteristics of chemical engineers, i.e. *the ability to apply molecular level understanding to convert raw materials into more valuable products by physical, chemical and biological transformations using economic and safe processes*, should remain unaltered. Thus the core subjects in the curriculum, involving mass and energy balances, thermodynamics, transport processes, reaction engineering, separations, laboratories and design, should continue in the future but with structural modifications as discussed below.

Expanded Examples of Applications

As noted above, chemical engineers now find employment in a wide variety of industries. It is apparent that their skill set, which includes chemistry in addition to physics and mathematics also available to the other engineering disciplines, makes them uniquely qualified to valuably impact a diverse set of technologies. However, the curriculum continues to include examples primarily from the petroleum refining, petrochemical and bulk chemicals industries. It is important to broaden the scope by including examples from areas such as materials processing, biotechnology, pharmaceuticals, food processing and environment. Similarly, when discussing design, considerations of product and not merely process should be included. These movements will require availability of new textbooks and teaching modules, and some steps in this direction are already being taken.

Modern Biology as an Underlying Fundamental Science

Recent developments in molecular and cellular biology, the similarity of utilizing biological and chemical reactions at the molecular level for design of new products and processes, and the growth of biotechnology industries where chemical engineers are currently employed and from all indications will be in greater numbers in the future, *all* suggest that biology will soon reach an almost equal status with chemistry as a basic science in defining chemical engineering. Thus, it is now timely to include one or two formal courses in biology and biochemistry in the early years of the undergraduate curriculum. This requires two types of actions: one, working together with the relevant disciplines to arrive at suitable courses and two, incorporating elements of biology within *all* the chemical engineering courses just as chemistry today. Thus, for example in the reaction engineering course, building upon knowledge of biochemistry and biology gained earlier, connections between molecular mechanisms and macroscopic kinetics could be made and related to modeling of cells and bioreactors, similar to what is done today with chemical catalysis and diffusion-reaction in catalyst pellets leading to fixed-bed reactor design. Similarly, based on biological understanding, separations courses can readily include living systems and processing of biomolecules. Numerous opportunities also exist in other core courses such as mass and energy balances, thermodynamics, transport processes and design. These developments are likely to take some time to materialize, but movement in this direction is critical for chemical engineers to contribute effectively and exercise leadership in the biotechnology areas that offer tremendous potential for growth.

Recruitment of Talented and Motivated Students

Since people are the greatest asset, for the vitality and future of the discipline, we must attract the best and the brightest to chemical engineering. This will occur naturally if we offer imaginative courses and programs involving new technologies, teach using newer methods and tools, and provide intellectual challenges for our students, so that they have promise of a bright future while solving important problems facing society.

A specific method that I have found to be effective in challenging students intellectually is by their involvement in undergraduate research. The opportunity to do an independent project with only general overall guidelines provided, often using equipment assembled on their own, is very stimulating for most students. Over the last 10 years, when I began to keep record of this activity, 25 undergraduates have conducted research in my laboratory, many starting with their junior year, and some 15 went on to attend graduate school elsewhere, mostly for PhD degrees. (In a light-hearted vein, I sometimes say that I have saved a large number of brilliant chemical engineers from leaving our profession for careers such as in medicine or law – of course, I do not say this in front of my daughters, one a lawyer and the other studying to become one!) Many work closely with a graduate student or a postdoctoral associate, to mutual benefit, and I have a number of journal papers with undergraduates as co-authors. Undergraduate research exposes students to the frontiers of the field, and provides the intellectual challenges that are difficult to match in typical lecture or laboratory courses.

Name Change of Departments

As noted in previous sections, the chemical engineering profession is changing rapidly and faces new challenges. The most impressive movement appears to be the emergence of modern biology as a fundamental science, on an almost equal footing as chemistry, in defining the field. Further, all indications are that its role will continue to grow in the future. For this and other pragmatic reasons, including that students are attracted to biological departments and degree names, and that we face new competition for students and resources from the appearance of bioengineering and biomedical engineering departments (some 90 such departments already existed at the end of 2001 [15]), many chemical engineering departments are changing their names to include some biological term. Among several that are possible, the name *chemical and biomolecular engineering* seems to be gaining acceptance, as adopted recently by departments at Pennsylvania, Cornell, Illinois and ours at Notre Dame. This name connects with the scientific base of the discipline, as compared with alternatives it is more inclusive of modern biotechnolgy and, owing to its molecular focus, offers more potential for collaborations with biochemists and biologists. Thus, while Juliet of William Shakespeare asks, "What's in a name? That which we call a rose, by any other name would smell as sweet," for the reasons cited, I favor departmental name changes.

Graduate Education and Research

Although I have limited my remarks so far to undergraduate education, I would like to now say a few words about graduate education and research. Graduate education started in the early 1900s as well, at both the MS and PhD levels. The core graduate curriculum has essentially mirrored that at the undergraduate level, with the former always being more fundamental and mathematical in content. Thus, courses in thermodynamics, kinetics and reaction engineering, transport processes and mathematical analysis, based on the engineering science approach, are currently required in most graduate programs. These are augmented by other courses in chemical engineering, various sciences, and other engineering disciplines, to suit the student's research needs and interests. Similar to the undergraduate ones, the graduate courses also need to include examples in newer application areas and incorporation of biology, particularly as it is introduced in the earlier years.

In research, chemical engineering graduate programs have moved forward rapidly to embrace all areas of new technologies, including biological, materials, environmental, information and energy. This movement was promoted by the National Research Council "Frontiers in Chemical Engineering" report published in 1988 [17], whose recommendations were reinforced and updated recently [18]. Further, there is a growing trend towards *interdisciplinary research*, involving faculty members and students from different fields working together to solve research problems. This trend has its origin in at least two related facts: one, the cutting-edge problems are often at the interface between disciplines, and two, funding agencies (now primarily federal and state, as compared to mainly industrial prior to the 1950s) seem to favor this approach. In turn, universities have responded by establishing research Centers, typically involving Colleges of Science and Engineering but sometimes also Business or Public Policy, that facilitate interdisciplinary interactions. While the co-existence of traditional departments and centers can lead to tension, I believe that organization along these lines is required and this structure is here to stay for some time.

Finally, there is another movement currently occurring in the chemical engineering discipline, particularly at the graduate education and research levels. On one hand, in addition to a molecular-level description of chemical and biological transformations and processes, there is growing feasibility now to also conduct molecular scale simulations to compute thermodynamic, transport and other properties of fluids and materials. On the other hand, owing to the strengths of analysis inherent in the engineering science approach, along with a systems view, it is possible to analyze complex systems and their interactions. These directions are changing the nature of chemical engineering such that it may be claimed that *molecular engineering of products and processes* is emerging as a *new paradigm* for the discipline. This movement will take some time to significantly influence the education of chemical engineers at the undergraduate level, and there is current discussion ongoing in this regard [15].

Concluding Remarks

Chemical engineering as a distinct discipline started with applications primarily in petroleum refining and bulk chemicals production industries. However, skills developed as result of a solid foundation in the fundamental sciences - chemistry, physics, mathematics and now increasingly, biology - along with a quantitative engineering science approach, have permitted chemical engineers to move rapidly into many emerging technologies. Their impact in the newer areas will be enhanced by continuing the core curriculum, and augmenting it by expanded examples of applications, incorporating biology in all core courses, and including orientation towards both product and process design. By offering imaginative courses using new teaching methods and tools, and by providing intellectual challenges, we need to attract the best and the brightest to chemical engineering, and educate them to become leaders in industry, academia and society.

I hope that these remarks, along with the current discussion ongoing with the NSF/CCR workshops [15], will lead to innovative chemical engineering programs that involve new technologies and provide a bright future for our students while solving important problems facing society.

Acknowledgements

I have benefited much from discussions with my colleague Mark McCready. Bob Armstrong and Barry Johnston of MIT helped immensely by providing information about the NSF/CCR Workshops. The Edison Lectures of Bob Brown, also of MIT, presented a few weeks ago at Notre Dame provided a valuable perspective in the evolution of chemical engineering. Finally, by collecting data from sources and designing slides, Chris Norfolk and Alexander Mukasyan helped with preparation of the lecture.

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