Curriculum Revitalization in Chemical Engineering

Summary

The discipline of chemical engineering has evolved dramatically over the past forty years, yet the core curriculum has undergone only minor changes. The engineering science paradigm that began in chemical engineering around 1960 still dominates the core curriculum and major educational texts used throughout the field. That paradigm has served us well; indeed, it has been enabling for chemical engineering to become a central engineering discipline[1]. The unique focus of chemical engineering on molecular transformations, processes, quantitative analysis, and multiscale treatment of problems provides an ideal platform for productive interactions with a wide range of other science and engineering disciplines at boundaries that are among the most exciting technology areas of our time. This broad applicability of chemical engineering fundamentals has become a defining feature of the discipline, and we are challenged to convey this breadth to our students. Hence a major driver for curriculum reform is the need to connect students to these many applications. Inasmuch as engineering curricula are often taught largely through example problems, this is a major undertaking if it is to be done well. A second major driver for curriculum reform in chemical engineering at this time is the advent of molecular biology. Our disciplinary focus on molecular interactions and transformations makes for a natural and exciting connection with molecular biology. Finally, we find ourselves in an era of rapid educational reform, in which both methods of engaging students in classrooms and laboratories are being reexamined and methods of incorporating new technology for education are being explored.

The opportunities for reform in chemical engineering curricula are so compelling and broad that an appropriate response requires wide-ranging participation across the entire discipline. In addition to providing a richer response to this opportunity, extensive engagement of the academic community will facilitate wide adoption of the results of the reform. Hence this proposal is directed to a broad planning exercise to engage the chemical engineering discipline in responding to the challenges of breadth, biology, and new teaching methods. This will be done through a series of workshops, broadly advertised to the community. The first workshop will be focused on (re)defining the core curriculum in chemical engineering, with the product being enumeration of themes for a series of smaller topical workshops in these core areas. The theme workshops are charged with developing proposals for creation of texts, web-based supporting material, and modular experiments, design problems, and subtopics for augmenting and supplementing subjects.

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[1] This view was inspired by the editorial E. Wasserman, ACS Comment, “The other Anaheim meeting: Chemistry as a central science,” *Chemical and Engineering News*, **76** (45), 95 November 9, 1998 [http://pubs.acs.org/isubscribe/journals/cen/76/i45/html/7645comment.html].

Introduction

Several factors combine to make this a critical time for re-evaluation and redefinition of the curriculum in chemical engineering: (i) the evolution of chemical engineering from a discipline tied to a single industry, the petro-chemical industry, to a discipline that interacts across a broad range of industries and technologies, (ii) the advent of molecular biology, which provides a second molecular science to serve as one of the pillars of chemical engineering, and (iii) the rapid developments of new understandings of learning and teaching methods in science and engineering. Responding to these fundamental changes in chemical engineering requires a broad engagement of the entire discipline, and this proposal takes such an approach. A series of workshops is described with the goal of developing a plan for new curriculum development in chemical engineering that addresses the three drivers identified above. The result of these workshops will be a proposal for funding specific curriculum development projects across a wide range of departments and with the serious engagement of industry.

This proposal is an outgrowth of a meeting of heads of chemical engineering departments in the United States that was held at the 24th annual meeting of the Council for Chemical Research (CCR) in Cincinnati during March of this year. This chemical engineering department chairs meeting focused on the need for unified action by the chemical engineering discipline in response to the issues noted above in order to maintain cohesiveness in the discipline and in order to respond fully and effectively to the opportunities afforded by these challenges. The approximately forty department heads at this meeting were most enthusiastic about participating in a discipline-wide response to this NSF program on curriculum reform in engineering. A group of nineteen department heads

Ludlow, Douglas	University of Missouri – Rolla
Baltzis, Basil	New Jersey Institute of Technology
Kilpatrick, Peter	North Carolina State University
Rousseau, Ronald	Georgia Institute of Technology
Anderson, Tim	University of Florida
LeVan, Doug	Vanderbilt University
Glatz, Charles	Iowa State University
Manke, Charles	Wayne State University
Martin, George	Syracuse University
O'Connell, John	University of Virginia
Anthony, Rayford	Texas A&M University
Hawley, Martin	Michigan State University
Olbricht, William	Cornell University
Kiran, Erdogan	Virginia Polytechnic University
Chambers, Robert	Auburn University
Collier, John	University of Tennessee, Knoxville
Grossmann, Ignacio	Carnegie Mellon University
Zukoski, Charles	University of Illinois at Urbana Champaign
Armstrong, Robert	Massachusetts Institute of Technology

agreed to serve as one of CCR's Action Network Groups in order to facilitate this project. This group will serve as the planning group for the proposed workshops, and this large group guarantees broad participation across the discipline. Of course, the proposed workshops are not limited to this group, and we will invite all departments to participate. Three members of this group – Robert Armstrong, Ronald Rousseau, and Charles Zukoski – agreed to write this proposal to seek NSF support. Although this proposal is being submitted through MIT for pragmatic reasons, the Council for Chemical Research (CCR) should be regarded as the sponsoring organization. This is appropriate because of CCR's mission in fostering collaboration across the chemical sciences and engineering sector.

Evolution of Chemical Engineering

The 1990s saw dramatic increases in enrollments in undergraduate programs in chemical engineering around the country, as a response to the increasing demand for chemical engineers in a variety of industries. The diversity of employment opportunities for chemical engineers today is illustrated in Fig. 1, which shows the initial job employment for bachelors degree chemical engineers in 2001. Though this proposal focuses on undergraduate education, similar issues exist in graduate programs; and employment trends for chemical engineers at the masters and doctoral degree levels mirror the plot in Fig. 1. The value of chemical engineers to these industries lies in the combination of process, molecular, quantitative, and systems approaches that chemical engineers bring to bear on these technologies.

The central role that chemical engineering plays today as an engineering discipline is depicted in Fig. 2. Most departments of chemical engineering in the United States grew up along the horizontal axis and this figure, that is, they developed from a merging of chemistry and mechanical engineering. Therefore, many of the early applications of chemical engineering naturally fell within the domains of applied chemistry and energy and transportation. In recent years many new industries have come to appreciate the need for process engineering and have realized the potential benefits to new products of molecular engineering coupled with multiscale analysis and process design. This leads naturally to the broad range of interactions between chemical engineering and essentially all other engineering and science disciplines that is depicted in Fig. 2. Clearly chemical engineering does not displace these other disciplines, but works cooperatively with them at the exciting interfaces that appear in the annular ring in this figure. It is clear from a picture such as Fig. 2, that exciting new technology developments require couplings of different disciplines. A clear message from this figure for curriculum revision is that we need to teach our students a well defined core set of fundamentals in our discipline along with an attitude that encourages collaboration across disciplinary boundaries.

At the same time as our graduates have been drawn into a broad range of new industries, the petrochemical industry with which we have been traditionally associated has been undergoing dramatic changes:

- The industry is becoming increasingly global.

- There have been many mergers of companies and product lines.
- Chemical companies are becoming life science companies and spinning off chemical units.
- Some chemical companies are becoming virtual companies, outsourcing services including research traditionally done in-house.
- Chemical engineering is no longer dominated by the petrochemicals/bulk chemicals businesses (as evidenced by Fig. 1).
- Employees no longer expect life-time careers with a single company; our graduates can expect to have multiple professional jobs during a career.

Curriculum reform must also address these issues, most critically the increasingly central role of biology in our traditional industries and the need to prepare our students for versatile, multifaceted careers.

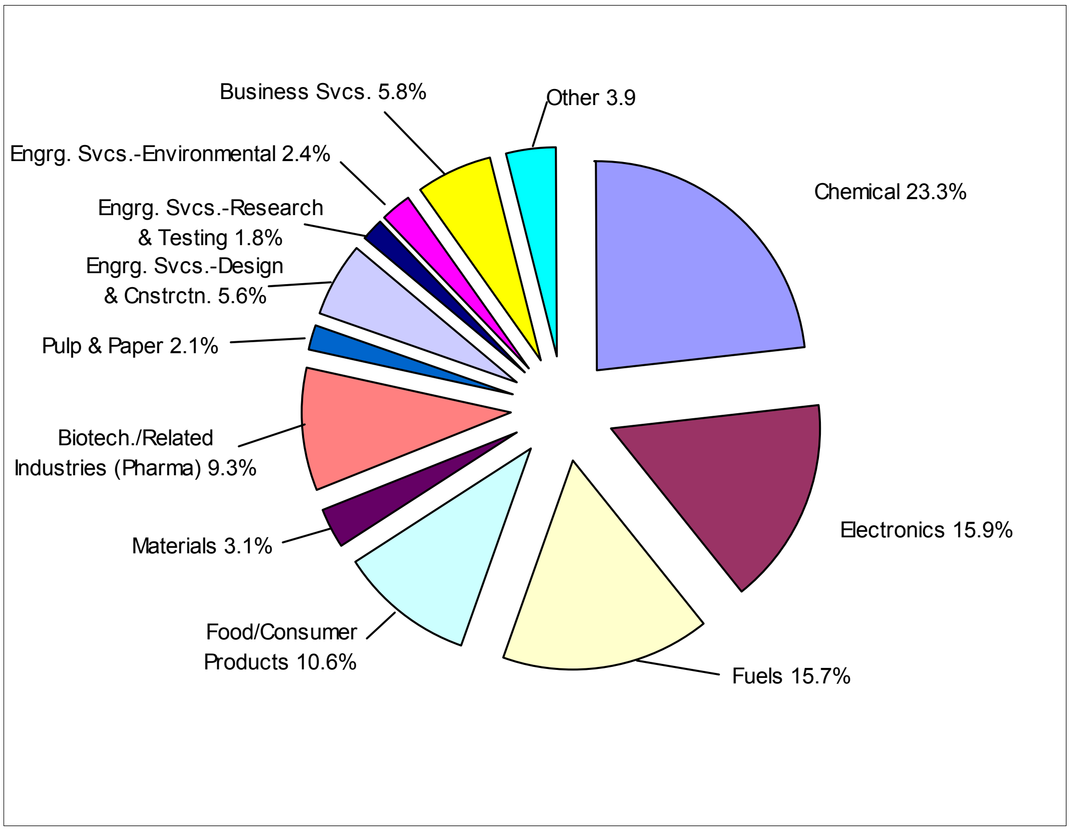

Figure 0. Industrial employment of B.S. chemical engineers starting in 2001. Data from AIChE Career Services (2001).

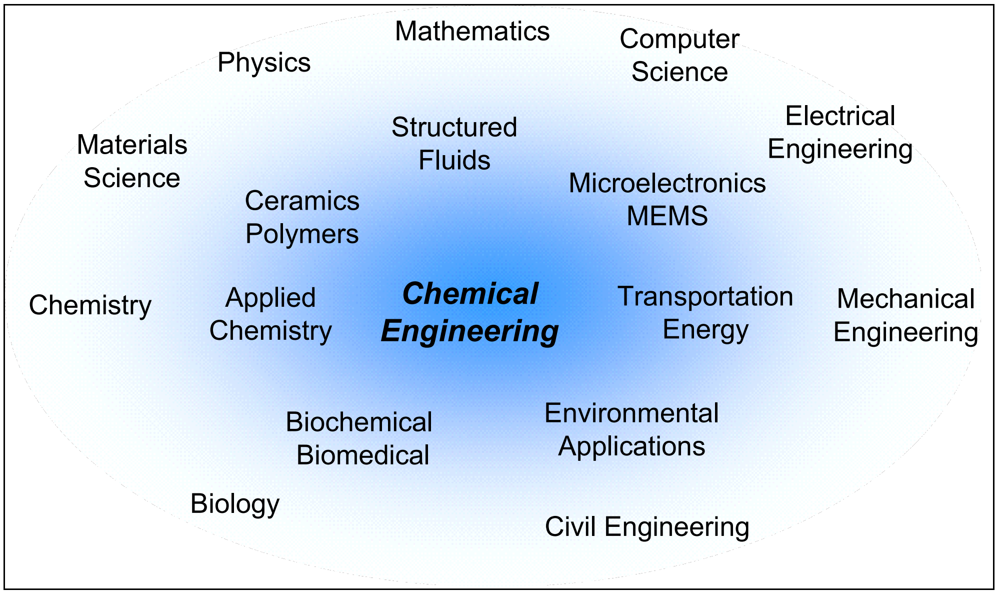

Figure 0. Chemical engineering has a unique position between the molecular sciences and engineering.

Biology as the Fourth Pillar of Chemical Engineering

The development of biology as a molecular science over the past two decades has provided a much more natural connection between biology and chemical engineering than has previously existed. Opportunities for taking knowledge of molecular interactions and reactions in biological systems and translating these into solutions of social and technological importance are numerous. The following list enumerates some of the problems to which chemical engineers are naturally positioned to contribute[2]:

- Bioprocess (biochemical reaction engineering, bioreactors with resulting bioseparations). Important in production of pharmaceuticals or commodity and energy products and are an integral part of waste treatment.
- Bioseparations. Supports bioprocesses, but is also of importance in medical applications such as cell separations (e.g., stem cell recovery) and proteomics (e.g., total analysis of protein content in a cell)
- Biocatalysis. Generation of protein catalysts with novel or enhanced activities, often in unusual environments.
- Metabolic engineering.
- Gene therapy – metabolic engineering combined with drug delivery. Quantitative problem requiring systems analysis.
- Biomaterials

[2] M. Shuler, Presentation to External Advisory Board, Department of Chemical Engineering, Carnegie Mellon University, May 8, 2002.

- Controlled release of bioactive compounds or surface modifications
- Tissue replacement
- Cell and tissue engineering combines biomaterials and broad concepts from metabolic engineering and analysis of chemical signaling. Manufacturing processes are similar to bioprocessing
- Drug delivery
- Drug/chemical metabolism predictions with physiologically based pharmacokinetic models
- Drug design and discovery (computational tools developed by chemical engineers for understanding protein-ligand interactions and chemical signaling in cells). Many other disciplines play here as well.
- Functional genomics or relating molecular or genomic information to cell function.
- Nano(micro)biotechnology, e.g., lab-on-a-chip devices.

Such a rich range of applications together with the natural fit as an underlying science for chemical engineering challenge the discipline to rethink fundamentally its core curriculum. Indeed this fundamental shift in core curriculum is mirrored in the renaming of many traditional chemical engineering departments to include biology explicitly as part of the name. For example, the departments at Cornell University and at the University of Illinois at Urbana Champaign have recently each been renamed the Department of Chemical and Biomolecular Engineering. The Department of Chemical Engineering at MIT has recently recognized this shift in its core science requirements, replacing one semester of organic chemistry with biochemistry; two core biology subjects are now required in the chemical engineering curriculum in additional to two restricted elective subjects.

New Educational Methods

Coupled with the fundamental intellectual drivers for curriculum reform in chemical engineering are the improvements in both mechanisms for delivering educational content through the web and also methods for more effective direct-contact education. The former is particularly important for this proposal, as the use of the web for delivering educational materials provides a mechanism for sharing educational developments across the wide spectrum of universities that we plan to bring together for this program. For example, the job of developing new examples for traditional subjects such as thermodynamics can be spread over many faculty, and the results shared over the internet. It is even possible to share the development of new laboratory experiments. See for example the web site used in MIT's subject 10.26, Chemical Engineering Projects, for doing heat exchange experiments over the web (http://heatex.mit.edu/)[3]. Students use the web interface to run actual experiments, not simply simulations of experiments. This

[3] MIT Tech Talk, May 22, 2002, p. 8. See also http://web.mit.edu/newsoffice/nr/2002/heatexchange.html.

experiment is currently used in a subject at the University of Texas, Austin, as well as at MIT.

Numerous educational studies have highlighted the importance of active learning in technical education. This impacts a curriculum reform such as that proposed here in several ways. First it is important to develop a set of design problems that can be used to introduce students to the breadth and opportunity of chemical engineering at an early stage in their academic studies. This is important for motivating the sequence of fundamental subjects that constitute much of the core curriculum. Second, the development of small, relevant examples for coupling with core subjects can substantially enhance understanding. Third, a broad range of design problems for use in capstone subjects in chemical engineering can provide valuable confidence to the students in how to apply chemical engineering fundamentals in new situations.

Proposed Planning Workshops

Prior to the beginning of the workshops proposed here, and as a follow-up to the Cincinnati chemical engineering department heads meeting, CCR and Shell Oil Company will co-sponsor a workshop in July at a Shell Oil conference facility near Houston (Woodlands). Shell Oil's CEO, Dr. Steven Miller has graciously agreed to host this workshop. The purpose of this workshop is to bring together leaders from academic departments, the broad array of industries served by modern chemical engineering, and government to develop a series of white papers addressing chemical engineering's roles and opportunities with respect to technologies based on the molecular sciences of chemistry and biology. These white papers will serve as excellent starting points for the workshops proposed here.

The Chemical Engineering Curriculum for the Future

The lead workshop for this curriculum reform planning project will focus on identifying key elements of the chemical engineering curriculum for the future, producing a road map for evolving core curriculum, and tasking a set of follow-on topical workshops described in the next subsection. Key issues to be addressed in this workshop include:

- The role of biology in the new curriculum. Clearly chemical engineering cannot, nor could any other discipline in an undergraduate program, embrace the full breadth of biology in its curriculum. Early on we need to choose those aspects of biology that fit together with chemical engineering's focus. We need to integrate clearly biology as a basic science and one of the four pillars of chemical engineering: biology, chemistry, physics, and mathematics. This requires, at a minimum, the major undertaking of meaningful integration of biologically based examples throughout the curriculum, e.g., biological reactions, separations, etc. We need to think about the inclusion of entirely new subjects, such as bioinformatics and systems biology.

- What is the right balance between fundamentals and applications in the curriculum? Chemical engineering has traditionally taught fundamentally focused curriculum, with the goal of preparing students to tackle new problems not envisioned at the time of their education. Clearly this is still paramount, yet we need to weave applications through out the curriculum in order to engage students actively in the learning process. This discussion should build on the themes of molecular transformations, quantitative understanding, systems treatment, and multiscale analysis, which have served chemical engineering well.

- How do we best connect to the breadth of applications illustrated in Fig. 2 in the curriculum? Our students need a strong sense of the versatile set of problems they are prepared to address.

- We need to strike a balance between the desire to teach our students many different topics and the need to use the diverse topics to prepare our students for the future.

- How do we attract the best and brightest minds to our discipline? A revitalized curriculum is key part of this, but we need to engage other groups, e.g., AIChE, in a campaign to get our message to the public. This is very important for ensuring a dynamic and well-educated essential segment of the workforce for the biotechnology, chemicals, and advanced materials industries of the future. A spin-off activity of this workshop will be connections with appropriate groups for help in articulating what we do to the public.

We will solicit wide spread participation in this initial workshop from chemical engineering educators and from the breadth of industries that hire our graduates now or that we expect to hire our graduates in the future. In addition, we will invite educational specialists to help ensure that the group is aware of recent advances in understanding of technical learning. Invitations will be sent to all chemical engineering departments in the U.S., and we will develop a list of industrial participants through the industrial members of CCR as well as through the industrial participants at the Woodlands workshop in July.

Topical Workshops

Small workshops will be organized in focus areas identified in the kickoff workshop. It would be presumptuous to identify or specify these topical workshops at this point. If we were organizing these topical workshops around a contemporary chemical engineering curriculum, the list might include:

- Introduction to Chemical Engineering
- Thermodynamics
- Transport processes
- Reaction engineering
- Separations
- Chemical Engineering Laboratories
- Design

The topical workshop in reaction engineering might then focus on a new subject built on a premise that all chemical engineers take biochemistry as well as organic chemistry as a prerequisite. Appreciation of processes at the molecular-cellular level could be emphasized and linked to the context of the reaction problem. Connections between molecular mechanisms and macroscopic kinetics could be made and tied to reactor and whole-cell modeling. Modular approaches to this subject would allow flexibility in adapting the material for use in a variety of chemical engineering departments where prerequisites may vary. Similarly, a chemical and biological separations subject might deviate substantially from a traditional subject as follows:

- Reduce emphasis on traditional separations
    - Concepts introduced through volatility based separations, staged processes, distillation with reflux, etc.
- Steady State Rate Processes
    - Membranes, RO, UF, diafiltration, cell and protein separations
    - Electrophoresis
    - Absorption, stripping, extraction (briefly)
- Fixed Bed Rate Processes
    - Adsorption and ion exchange
    - Chromatography - HPLC, GPC, affinity, reverse phase, etc.
- Miniaturization of separation processes

The topical workshops will be charged with developing specific plans for distributed production of educational texts, modules, design problems, etc. in the respective topical areas.

Summary workshop

The final workshop proposed here is designed to bring the different topical groups back together to ensure integration and coherence of the overall curriculum development plan. In order to maximize participation by the chemical engineering community in this summary workshop, we plan to hold it in conjunction with an annual meeting of the American Institute of Chemical Engineers. The goals of this final workshop are

- to disseminate of plans developed in the topical workshops for specific curriculum development;
- to solicit response from the broad chemical engineering community, including members from academia, industry, and government; and

- to finalize and coordinate plans for the follow-on proposal for actual development of new curriculum.

We expect to use a similar vehicle in ensuing years to keep the chemical engineering community up-to-date on the curriculum reform project.

Conclusion

The emergence of biology as a molecular science, the evolution of chemical engineering into a central engineering discipline, and the increased understanding of technical education methods make this an opportune and critical time for significant curriculum reform in chemical engineering. This proposal is focused on widespread participation by the chemical engineering community in this exciting and crucial activity. From the series of workshops proposed here, a road map for curriculum reform and specific new curriculum development projects will be developed. These will be proposed to NSF in the follow-on proposal cycle. The broad participation achieved in this proposal is essential to ensuring that the curriculum development efforts find widespread use.