A Vision of
THE CURRICULUM OF THE FUTURE

ROBERT C. ARMSTRONG
Massachusetts Institute of Technology • Cambridge, MA 02139

Over the past 40 years, the discipline of chemical engineering has undergone dramatic changes. We are no longer a discipline largely coupled to a single industry, namely the petrochemical industry. Rather our graduates go to a wide variety of industries including chemicals, fuels, electronics, food and consumer products, materials, and biotechnology and pharmaceuticals.[1]

Moreover, the character of the chemical industry has changed significantly, particularly in recent years:

- *the chemical industry is today very much a global enterprise;*
- *companies have been reshaped by a series of mergers, acquisitions, and spin-offs;*
- *some major chemical companies have become life science companies and spun off their chemical units;*
- *and the time-to-market for new products has been significantly shortened.*

Similarly, the research enterprise in chemical engineering has exploded over the past 40 years both in dollar volume and in breadth. The exciting research opportunities that we explore today as a discipline were well illustrated in the "Future of Chemical Engineering Research" sessions at the 2004 Annual Meeting of AIChE. Particularly notable shifts in research over this period include much more biologically related research and a much stronger molecular perspective in the research.

Over this same 40-year period the undergraduate curriculum in chemical engineering has remained nearly unchanged. The stagnation in the curriculum is well illustrated by Figure 1, which is taken from a paper by Olaf Hougen.[2] The flow chart in the figure shows the evolution of the curriculum decade by decade from 1905 to 1965. In each decade, new content entering the curriculum is shown as well as material that was removed in order to "conserve mass." The center of each box defines a core theme(s) for the decade.

I would like to make two observations about this figure. First, over the 60 years shown, the curriculum was very dynamic with significant changes in each decade. Second, by 1965 we had developed a curriculum for undergraduate education that is very nearly the same as today's. Why is this? It is possible that after 60 years of hard work on the curriculum the discipline arrived at a more or less timeless implementation. But this seems hard to believe in the face of all of the change that has taken place over the past 40 years outside of the curriculum. On the other hand, it is possible that we have simply not paid the attention we should to curriculum development over this period. This is what I believe has happened. This same period has seen an enormous growth in federal research funding in universities, and this growth is reflected in the large number of doctoral research programs in chemical engineering around the country. This research has created valuable intellectual growth in our community, but it consumes an enormous fraction of the time of our faculty members just to keep the research engine running, with grant pro-

__Robert C. Armstrong__ is Chevron Professor and head of the Department of Chemical Engineering at the Massachusetts Institute of Technology. He received a B.ChE. from the Georgia Institute of Technology in 1970, and a Ph.D. in chemical engineering from the University of Wisconsin in 1973. His research interests lie in the areas of polymer molecular theory, polymer fluid mechanics, rheology, multiscale process modeling, transport phenomena, and applied mathematics. He is co-author of the two-volume text Dynamics of Polymeric Liquids*, which has been named a Citation Classic.*

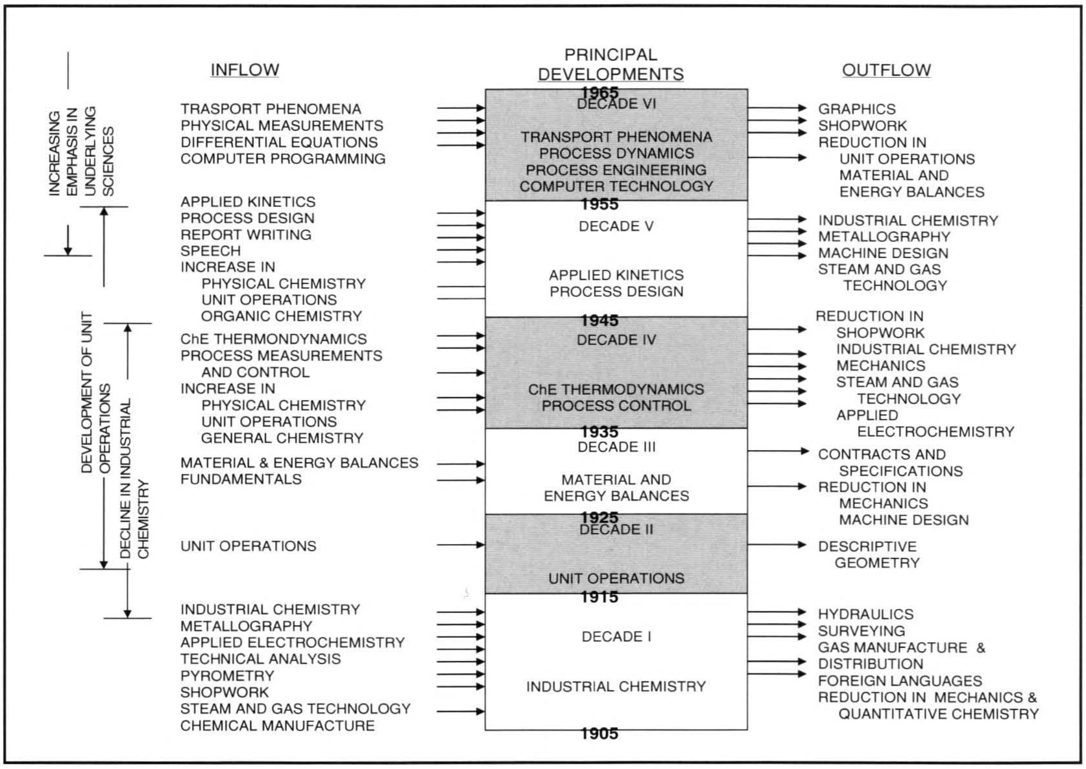

Figure 1. *Changes in a typical undergraduate chemical engineering curriculum during 60 years. The initial curriculum in 1905 consisted of separate courses in chemistry and conventional engineering.*[3]

posals, contractors' meetings, review panels, annual reports, etc. The price has been neglect of the curricular content in chemical engineering and a widening gap between the research done in modern chemical engineering and the content taught in our undergraduate programs.

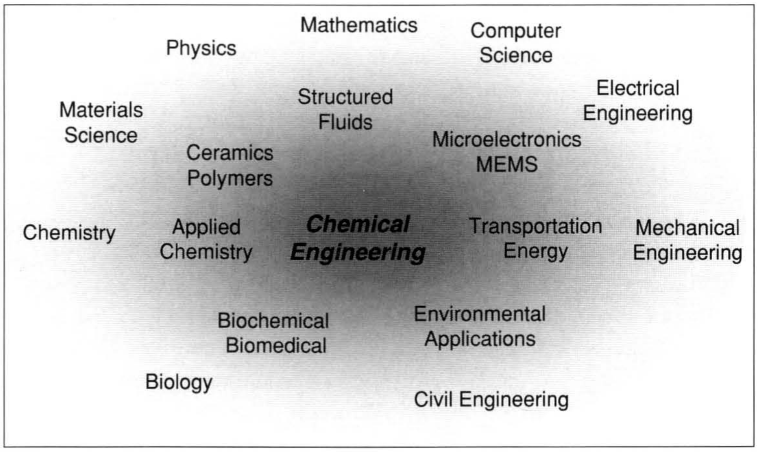

Figure 2. *Chemical engineering has a special position between the molecular sciences and engineering.*

The opportunities for chemical engineering today are great (see Figure 2). We are uniquely positioned at the interface between molecular sciences and engineering, and this affords us many opportunities in a broad range of technologies that lie at the interface between chemical engineering and other science and engineering fields. This image of chemical engineering creates a number of tensions in our curriculum. There is a strong outward pull on our curriculum toward the many disciplines with which we interact at the interfaces in Figure 2. The opportunity to teach our students more about these particular areas of technology is exciting educationally, but it does tend to have a fragmenting effect on the discipline. Opposing the strong outward pull is an equally compelling need to look inward at the core of chemical engineering. Some departments have dealt with this tension by developing curriculum tracks in specialized areas. Students begin by taking a common core in chemical engineering and then specialize in a number of technology areas, *e.g.*, biotechnology, materials. An alternative approach, proposed here, is to refocus on the core content of chemical engineering. Thinking clearly about what constitutes the core of chemical engineering that will make our future graduates key contributors in interdisciplinary problems is essential. It is important to remember that the current core we teach was developed when chemical engineering was described by the horizontal axis in Figure 2. That is, chemical engineering was dominated by the intersection of chemistry and mechanical engineering. We need to reexamine whether that core is the appropriate core for the two-dimensional image in Figure 2. The broad range of applications of chemical engineering can be included in the curriculum by way of examples, problems, case studies, and laboratories. In this way we maintain a common education for all chemical engineers that demonstrates the versatility of the degree to all of our students.

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CCR/NSF FRONTIERS IN CHEMICAL ENGINEERING EDUCATION WORKSHOPS

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. This is important for a number of reasons. First, the opportunities/frontiers are too broad for any one department or several departments to address effectively. Second, the costs—time and money—of developing new educational materials are too high for any of us to absorb alone. Finally, the coherence resulting from a joint effort will serve the discipline well in maintaining a clear identity to the world (potential students, industry, and government), ensuring good manpower supply to industry and to our graduate programs, and ensuring that curriculum developments are used.

Nearly 100 faculty members from 53 universities along with industrial representatives from five different companies met in a series of three workshops sponsored by the Council for Chemical Research and the National Science Foundation to discuss curricular opportunities and to map out a path forward. Below I will highlight some of the key findings of the workshops. I encourage you to look at the detailed work product and proceedings from these workshops, which can be found at <http://mit.edu/checurriculum/>.[3]

Before I begin with the summary of the workshop results, I would like to relate an interesting observation made by many of us at the workshops: if we think about the curriculum in the large blocks we usually use—thermodynamics, transport phenomena, kinetics, etc. —then change will be difficult or impossible. The reason is very simple. The current curriculum is full (or overflowing); if we take these large units to be givens in a new curriculum, then there is simply no room for new content. Hence we felt it worthwhile and important to put everything on the table and to start with a clean slate in thinking about the future. We asked ourselves, what should a "Decade XI" box covering the years 2005 to 2015 look like if we were to extend the Hougen analysis?

Principles

The first valuable lesson to emerge from the workshops was a set of principles that captured well the consensus of the group. These included:

- *Changes in science and the marketplace call for extensive changes to the chemical engineering curriculum*
- *The enabling sciences are: biology, chemistry, physics, mathematics*
- *There is a core set of organizing chemical engineering principles*
    - *Molecular transformations, multiscale analysis, systems*
        - *Molecular-level design is a new core organizing principle*
- *Chemical engineering contains both product and process design*
- *There is agreement on the general attributes of a chemical engineer*

Two of these elements need elaboration: the core organizing principles and the attributes of a chemical engineer.

Organizing principles

In order to arrive at a picture of the curriculum we began by enumerating the content—rather than the labels—that chemical engineering graduates should understand and be able to use. By then looking at the linkages and interconnections among these content elements, **three organizing principles** for the chemical engineering curriculum emerged. These are molecular transformations, multiscale analysis, and systems analysis and synthesis.

At the heart of chemical engineering is the manipulation of molecules to produce desired processes and products. This is encompassed by the organizing principle of **molecular transformations**. Our students must recognize by both qualitative reasoning and quantitative computation that properties can be changed by changing structure. Molecular changes can be architectural, for example by forming or breaking covalent bonds or by secondary or tertiary interactions to form superstructures. Or molecular changes can be conformational, for example in the orientation and stretching of polymer molecules to change mechanical properties or in the folding of proteins. Chemical engineers need to understand the equilibrium properties of these molecular systems and the rates of reaction or structural changes. Finally our graduates should be equally comfortable with the manipulation of biological molecules as with the small organic and large synthetic polymer molecules that have been the traditional domain of chemical engineering.

It is not sufficient for chemical engineers to manipulate matter at the molecular level. In addition we must be able to connect behavior at the small scale with that at the large scale. For example, we need to be able to take the molecular-level understanding of the kinetics of a chemical reaction and use this to design an appropriate reactor for commercial use. Or we need to be able to exploit the understanding of polymer conformation on properties in order to design a commercial spinning process to make high-strength fibers. The organizing principle of **multiscale analysis** addresses the application of chemical engineering principles over many scales of length and time. It is not the goal of multiscale analysis to have students work from the atomic or molecular level up to the macroscopic level in every problem. Rather, it is important that students develop the ability to recognize, in any given problem, what the important length and time scales are for analysis and design.

- Molecular Scale Transformations
  - chemical & biological
  - physical: phase change, adsorption, etc
- Multi-Scale Descriptions
  - from sub-molecular through "super-macro"
  - for physical, chemical and biological processes
- Systems Analysis & Synthesis
  - at all scales
  - tools to address dynamics, complexity, uncertainty, external factors

Old core does not integrate molecular concepts

Old core covers only macro to continuum, physical and chemical

Old core primarily tied to large scale chemical processes

Figure 3. *New organizing core principles for use in integrating the curriculum.*

Ultimately chemical engineers cannot be successful unless we can take the knowledge of molecular processes and the ability to manipulate these across appropriate scales and integrate these into functional systems. The organizing principle of **systems analysis and synthesis** deals with the tools for synthesis, analysis, and design of processes, units, and combinations of these. The systems of importance to chemical engineers cover a range of scales. They could be single cells in which we manipulate and control metabolic pathways to produce desired chemical products, or they could be the entire globe or large regions of the globe in which we desire to regulate sources of emissions in order to control concentrations of undesirable chemical species.

In summary, chemical engineers leverage knowledge of molecular processes across multiple-length scales in order to synthesize and manipulate complex systems comprising processes and the products they produce. These new principles are summarized in Figure 3.

Attributes

Engineers are fundamentally problem solvers, seeking to achieve some objective of design or performance among technical, social, economic, regulatory, and environmental constraints. Chemical engineers bring particular insights to problems in which the molecular nature of matter is important. As educators we cannot teach students everything that might be encountered; instead we aim to equip graduates with a confident grasp of fundamentals and engineering tools, enabling them to specialize or diversify as opportunity and initiative allow. We seek in our curriculum to develop critical thinking and problem solving skills, especially for open-ended problems and those with noisy data or uncertain parameters; to cultivate professional attributes including oral and written communications skills; to broaden the technical base of the students by including examples from a variety of industries; and to cultivate an instinct for lifelong learning and an awareness of the social impacts of engineering and technology. The need for agile, inquisitive, and fearless engineers is strongly reinforced in the *Molecular Frontier* report on chemical sciences and engineering,[4] which points out that the cutting-edge knowledge of chemical engineering practice across industries is changing constantly, as are global networks of technology development.

In working to create a curriculum for the future, it is our challenge to set a national vision for chemical engineering graduate practice beyond the norm, at the level described by several national commissions on engineering education that envision engineering graduates who are able to use fundamental knowledge of science and engineering in a flexible and creative manner. The *Molecular Frontier* report[4] envisioned future graduates who can meet the following challenges:

- *Understand the basic chemistry of traditional chemical processes, living systems, advanced materials, and environmental control.*
- *Synthesize and manufacture any new substance that can have scientific or practical interest, using compact synthetic schemes and processes with high selectivity for the desired product, and with low energy consumption and benign environmental effects.*
- *Revolutionize design of chemical processes to make them safe, compact, flexible, energy efficient, environmentally benign, and conducive to the rapid commercialization of new products.*
- *Understand and control, to the limits of current knowledge and tools, how molecules react over all time scales and the full range of molecular size.*
- *Develop unlimited and inexpensive energy, with new ways of energy generation, storage, and transportation to pave the way to a truly sustainable future.*
- *Communicate effectively to the general public the contributions that chemical engineering makes to society.*
- *Be able to work in an interdisciplinary team of scientists, engineers, and production personnel to bring new substances from lab to production to market.*

A Draft Curriculum

The curriculum must engage students in the subject matter of chemical engineering and its use, and cultivate along the way that mix of attributes that characterizes the engineer. To accomplish these goals we envision a four-year structure that emphasizes the themes of chemical engineering, integrates the contents of these themes into a flexible and strong understanding, and exercises the skills we want to develop. This structure is versatile, admitting a variety of materials and modes of presentation, and is thus adaptable to a range of cultures, resources, and facilities found among chemical engineering departments.

I do not have a finished structure of a curriculum to present; we are not yet that far along. At the third workshop held on Cape Cod, however, we developed a draft curriculum as a "proof of concept" to convince ourselves that this was possible. Shown in Figure 4 is the layout for a curriculum that develops the three organizing principles—molecular transformations, multiscale analysis, and systems analysis and synthesis—in parallel throughout the undergraduate years, and shows how the three themes are integrated in chemical engineering practice.

The content must also be integrated horizontally through time, so that each principle is clearly developed. It is important to provide many opportunities for repetition of key ideas, concepts, and tools as the students move through the four years of curriculum. The reinforcement of these key elements should also be accompanied by a systematic movement from simple to complex topics as the curriculum proceeds. Content must also be integrated vertically at given times in order to avoid compartmentalization. One way to achieve this vertical integration is to use part of each year for case studies, projects, or laboratories that cut across the three themes. For example, each theme in the core curriculum could be presented in one-and-a-half-semester subjects. In the latter half of the spring semester each year, students could work in teams on intensive, integrated laboratory or design projects that enable them to take the material learned that year and apply it in projects developed by industry/academic project members. In this way, both the teaching and learning of the integrated core would be addressed. Integration could be further enhanced by a small-group seminar series (possibly appended to an existing subject) that develops important abilities of social awareness,

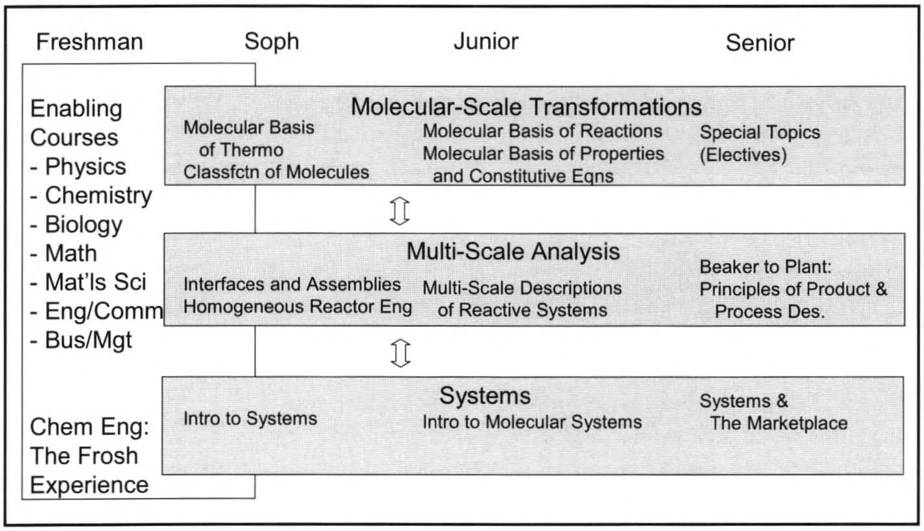

***Figure 4.** An example layout of a curriculum.*

professional ethics, communication, business development and professional practice, and economics. By focusing each seminar series on these important nontechnical abilities, students would hone these skills and be better able to apply them as part of their spring semester integrated project work.

In summary, the material within an academic term, as well as across the four years, must proceed from simple to complex. Fundamentals must be illustrated with applications, and examples must range from the simple demonstration to the challenge of complex design or system manipulation. Finally, students must be engaged actively with this material. At the end, the curriculum must add up to a complete picture of chemical engineering. The detail given in each principle block suggests an order of topics. Detailed definition of these blocks is the subject of ongoing workshops.

CONCLUDING REMARKS

This paper proposes a vision for chemical engineering education for the future—for 2015 and beyond. To return to the Hougen analysis of the chemical engineering curriculum shown in Figure 1, I am suggesting a structure and focus for Decade XI as illustrated in Figure 5. Because we have not engaged in substantial curriculum revision in 45 years, I believe that we are best served by beginning with a clean slate. For outflow, I suggest the entire current curriculum. This is not to say that there are not key elements of what we teach today that should be retained, but rather everything in the existing curriculum must compete with new ideas to win a spot in the new curriculum. As illustrated in the figure, the Decade XI curriculum would be organized around the organizing principles of molecular transformations, multiscale analysis, and systems analysis and synthesis.

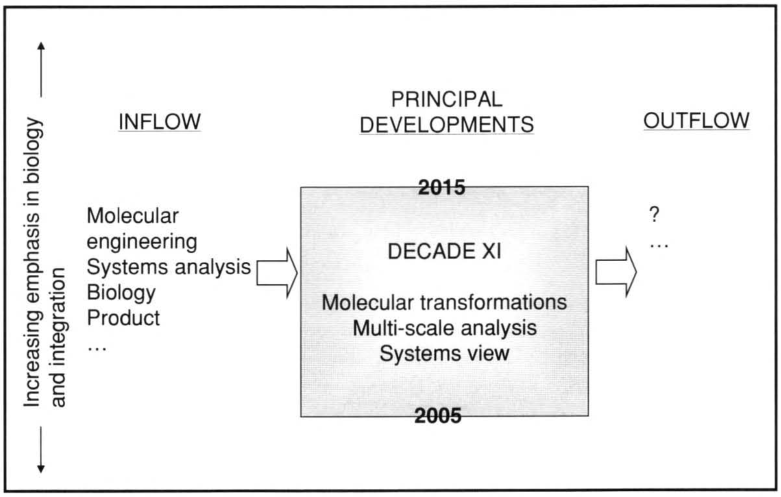

Figure 5. *The proposed extension to Hougen's chart.*

This radically different curriculum would produce more versatile chemical engineers, who are needed to meet the challenges and opportunities of creating products and processes, manipulating complex systems, and managing technical operations in industries increasingly reliant on molecular understanding and manipulation. Another benefit of the new curriculum is that it reconnects undergraduate education with ongoing research in chemical engineering in a way that has not been present for the past 40 years. This reconnection will serve us well as an engineering discipline in attracting the best and brightest students and in reopening the path to continual renewal of the curriculum.

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In writing this paper I have drawn very heavily on the collective thinking at the Frontiers Workshops. It is impossible to emphasize too strongly how much we have to learn from one another as we move forward in this great adventure. I want to give special thanks to the participants who synthesized summary reports at each of these workshops—Nick Abbott, Jeff Reimer, Jim Rawlings, Mike Thien, Greg McRae, and Bill Green—and to Barry Johnston, who prepared all of the material for the Frontiers Web site including the excellent executive summaries. Finally I thank Jeannette Gerzon who has ably helped organize and facilitate these workshops to help us be productive.

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