Frontiers in Chemical Engineering Education

Summary

A dramatic shift in chemical engineering undergraduate education is proposed, based on discipline-wide workshop discussions that have taken place over the past year, to be developed and implemented over a ten-year period. Through this process broad concensus has been developed regarding basic principles for chemical engineering undergraduate eduction in the future; these principles address fundamental knowledge, skills and attributes, and methods of engagement with the students. From these principles a new set of organizing principles emerged for the discipline: **molecular transformations**, broadly interpreted to include chemical and biological systems and physical as well as chemical structural changes; **multiscale analysis**, from sub-molecular through super-macroscopic scales for physical, chemical, and biological systems; and a **systems approach**, addressed to all scales and supplying tools to deal with dynamics, complexity, uncertainty, and external factors. The curriculum integrates all organizing principles and basic supportive sciences throughout the educational sequence and moves from simple to complex. The curriculum is consistently infused with relevant and demonstrative laboratory experiences, and opportunities for teaming experiences and use of communication skills (written and oral) are included throughout. The curriculum is also designed so as to address different learning styles and to include a first-year chemical engineering experience. Finally an important theme is a consistent infusion with relevant and demonstrative examples, which provide open-ended problems and case studies and supply frequent integrative opportunities for students. The proposal describes in more detail the rationale, the work plan to develop the new curriculum, and the steps that are envisaged to create modern case studies. The proposal is broad, ambitious and specifically designed to be inclusive – our future is at stake. The proposed curriculum development will be managed through an ERC-like structure, which coordinates the activities across the discipline.

There are several aspects to the broader impact of this proposal. First, the very thesis of the approach proposed here is that substanative, dramatic change in undergraduate chemical engineering education cannot take place without broad involvement of the discipline. Without a coordinated shift in direction for the discipline, it is unlikely that any one or several departments would depart radically from the current, commonly shared core curriculum. The common core that has been shared across chemical engineering since its inception is viewed as a very positive unifying feature, and the proposed cooperative effort will preserve this. Second, the broad range of curriculum development and experiments coupled with assessment and valuation as integral parts provides an enormous laboratory for studying how chemical engineers learn. By working together, we can engage more ideas and experiments on education and share best practices widely across the discipline. Third, no single department has the resources, either time or money, to engage in this depth of change. Human resources are most critical, and this proposal provides a mechanism to leverage scarce time across the discipline.

Of course, one of the primary drivers for the curricular change is to meet the future manpower needs of core technology industries important to the economic well being of the US. Much more versatile chemical engineers 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.

Frontiers in Chemical Engineering Education

1. Introduction and Motivation

Although historically focused on the petrochemical sector the Chemical Engineering profession has evolved to a point where it is now critical to such other sectors as microelectronics, medicine, biotechnology, and new materials. While demands for well trained engineers have continued to grow, our educational programs have not kept pace – it is time for change if the profession is to remain vibrant and attractive to young students and prospective employers and if we are to play a leading role in meeting the manpower needs in the emerging technologies and industry sectors that depend on molecular transformations. In the 1920s a group of chemical engineers met to create “The Literature of a Profession.” These books and the ones that followed in the 1950s and 1960s emphasizing engineering science have become the cornerstones of the current chemical engineering curriculum. Unfortunately these teaching materials do not reflect that dramatics advances that have taken place in the underlying sciences of chemistry and biology, nor do they capture the exciting frontiers of research in modern chemical engineering. This year three workshops were held to assess our curriculum. Faculty from more than 53 universities and industry representatives from 5 companies reached strong consensus that there is a need for change and that a large change is needed rather than incremental tweaks to the existing curriculum.

Through this process broad concensus has been developed regarding basic principles for chemical engineering undergraduate eduction in the future; these principles address fundamental knowledge, skills and attributes, and methods of engagement with the students. From these principles a new set of organizing principles emerged: **molecular transformations**, broadly interpreted to include chemical and biological systems and physical as well as chemical structural changes; **multiscale analysis**, from sub-molecular through super-macroscopic scales for physical, chemical, and biological processes; and a **systems approach**, addressed to all scales and supplying tools to deal with dynamics, complexity, uncertainty, and external factors. Set out below is a more detailed discussion of the rationale, the work plan to develop a new curriculum, and the steps that are envisaged to create modern case studies. The proposal is broad, ambitious and specifically designed to be inclusive – our future is at stake.

1.1. Drivers for Change in Chemical Engineering Education

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, multiscale, quantitative, and systems approaches that chemical engineers bring to bear on these technologies.

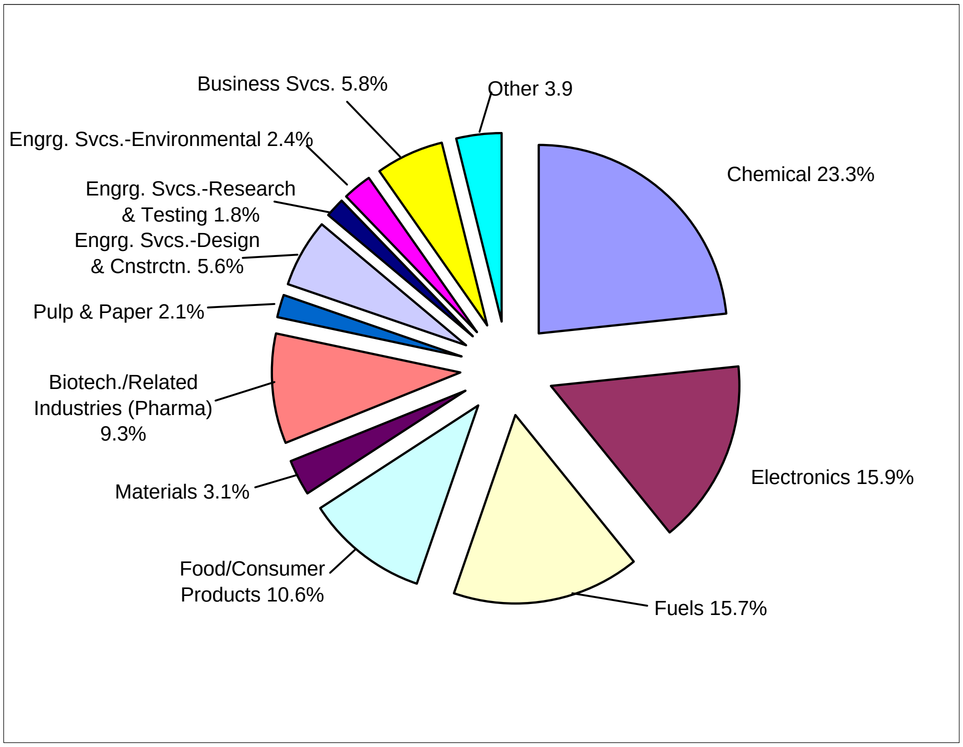

Figure 1. Industrial employment of B.S. chemical engineers starting in 2001. Data from AIChE Career Services (2001).

The 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 in 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 co-operatively with them at the exciting interfaces illustrated 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. In order to supply the manpower to fuel these emerging technologies and industries, we need an undergraduate curriculum that educates our students with 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.

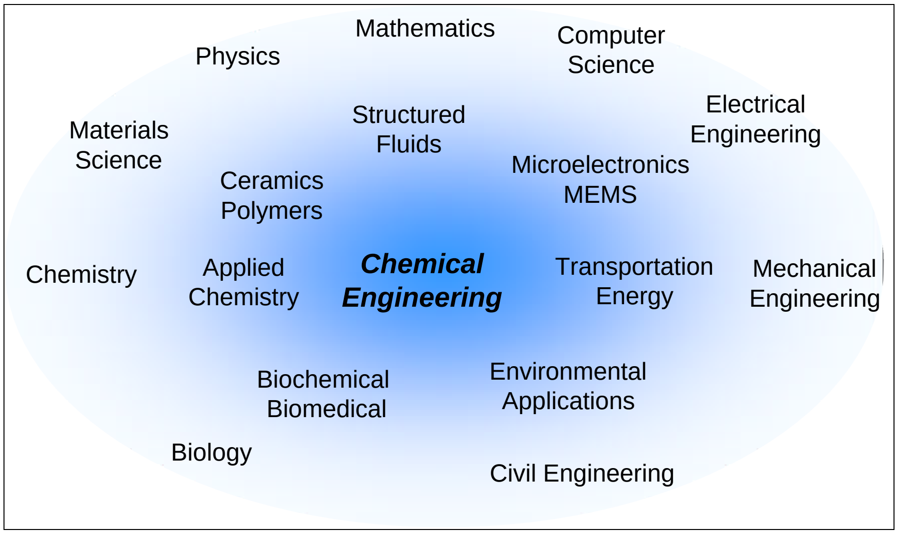

Figure 2. Chemical engineering has a unique position between the molecular sciences and engineering.

- Chemical engineering is no longer dominated by the petrochemicals/bulk chemicals businesses (as evidenced by Figure 1).
- Employees no longer expect life-time careers with a single company; our graduates can expect to have multiple professional jobs during a career.
- Product cycles have dramatically decreased; time-to-market has become critical.

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.

1.2. Educational Frontiers for Chemical Engineering Education

The three-workshop series titled "New Frontiers in Chemical Engineering Education" involved 84 chemical engineers representing 53 universities and five companies. Its results were a set of principles guiding chemical engineering education in the future, new organization of the subject matter of chemical engineering, and the consequent structure of a new curriculum, supplemented by examples of instructional modules. [See http://web.mit.edu/cheme/temp_files/che_workshop/index.html for full proceedings of these workshops.]

Workshop participants defined the scope of what chemical engineers do and described the elements of an undergraduate chemical engineering education without using the conventional categories. **Three organizing principles** emerged: first, chemical engineers seek to understand, manipulate, and control the molecular basis of matter, and the molecular-level processes – physical, chemical, and biological – that underlie observed phenomena in nature and technology. **Molecular Transformations** is a unified treatment of phenomena at this level.

Second, chemical engineers have been effective because we combine macroscopic engineering tools with a molecular understanding of nature. This naturally leads to an organizing principle of **Multiscale Analysis**. In this principle we compare and contrast the tools appropriate to a given length scale (molecular dynamics, continuum equations, macroscopic averages), gain an appreciation for the ways in which a given application can depend on phenomena occurring at different scales (a packed bed reactor, from kinetic mechanism to heat duty), and an understanding of the implications of phenomena at one scale for another (molecular structure affects macroscopic properties). Here also we contrast transient and steady processes.

Third, realistic chemical engineering problems (that is, the dynamic behavior of batch and continuous processes and systems in nature, technology, and society) feature multiple interacting components and also draw from fields outside chemical engineering. The *analysis* of such problems depends on coordinating a variety of tools. The understanding that emerges from this understanding leads to the ability to *manipulate* systems to achieve desired behavior or performance. Furthermore, chemical engineers design and create products and processes, so that there is a strong component of *synthesis*, as well. Hence we define the organizing principle of **Systems Analysis and Synthesis**.

In summary, the chemical engineer leverages knowledge of molecular processes across multiple length scales in order to synthesize and manipulate complex systems comprising processes and the products they produce.

2. Overview of 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 desire to elicit. 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.

2.1. Goals

Engineers are fundamentally problem solvers, seeking to achieve some objective of design or performance among technical, social, economic, regulatory, and environmental constraints. The chemical engineer brings particular insight to problems in which the molecular nature of matter is important. Educators 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:

- Cultivate professional attributes, such as willingness to make estimates and assumptions, readiness to face open-ended problems and noisy data, and a habit of visualizing the solution. The graduate should have the desire for life-long learning, an instinct to add value to an enterprise, an appreciation for the social impact of engineering, a willingness to engage other professions, a commitment to professional ethics.
- Hone the professional skills of problem solving; communication by oral, written, and personal means; working in teams; estimating uncertainty; using computational tools; economic analysis; and the ability to plan, execute, and interpret experiments.
- Broaden experience by examples drawn from a variety of industries. The newly-graduated engineer should be able to understand the mentoring of a senior engineer, have a knowledge framework on which to place the specific technology of the company, have worked examples in school that bear some relation to the company's operations, and have practiced the skills of technical approach, human relations, and communication that will be further refined in the workplace. She or he should feel confident that the core education can be augmented with problem specific learning to enable progress in new areas. We seek to graduate an engineer who is "fearless," one who embraces new challenges.

- Integrate the material to aid an overall understanding of chemical engineering. A good curriculum structure will leave the student at the end of each year feeling capable of practicing engineering at some level and excited about doing so.

2.2. Structure

We cultivate important attributes and skills during the study of chemical engineering. Chemical engineering topics teach the student how to deal with non-linear problems under competing constraints with insufficient information requiring multiple levels of attack. We propose that a curriculum be built to emphasize the principles of molecular transformations, multiscale analysis, and systems analysis, manipulation, and synthesis. The layout is shown in Fig. 3.

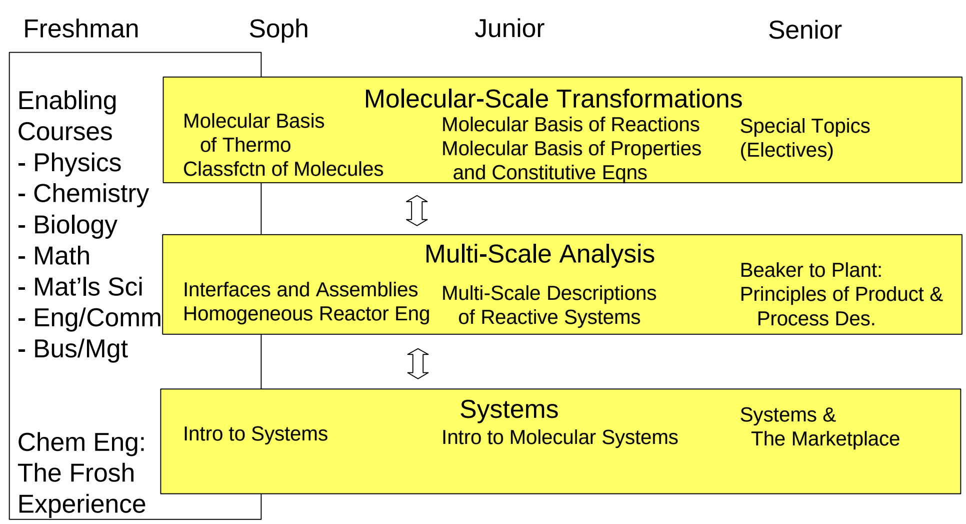

Figure 3. Example four-year undergraduate curriculum in chemical engineering.

The challenge of curriculum development is to specify the content of each of these blocks. The content must be integrated horizontally through time, so that each principle is clearly developed. Content must also be integrated vertically at any time in order to avoid compartmentalization. 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. Further specification of this content, along with development of the materials to present it, is the task to which this proposal is addressed.

2.3. Versatility

After the topics are placed in order, resource materials and the mode of presentation must be chosen. The curriculum of Figure 3 is flexible and admits of a variety of modes to be adaptable to a variety of universities. Three are suggested below, and more could be envisioned.

- The topics are arranged in full-term lecture courses that fit into traditional university course scheduling. For example, Molecular Processes I, II, and III might be fall term courses presented in the sophomore through senior years. Laboratories may be separate courses, or coupled with lecture courses.
- The topics are arranged as modules of varying length. A module called “Water Purification” might be followed by another called “Catalytic Cracking”, both running concurrently with a longer one called “Drug Delivery”. The content of these modules, if offered in the sophomore year, would differ markedly from senior modules by the same names. The topics of modules would differ according to faculty expertise, but they would be responsible to present certain molecular, multiscale, and systems content so that the overall integrity of the curriculum could be assured.
- Students encounter a succession of case studies. Each of these requires technical analysis, teamwork, communication; some require design and interaction with other disciplines, others are laboratory modules. Fundamentals are introduced to support the objectives of the case. The technical topics are drawn from a wide range of industries. The early cases are relatively simple; the latter more complex. Later case studies may return to the topic of an earlier one, but with a different and more difficult objective.

The standard resource material has for many years been the textbook, and the instructor charged to teach a course on a particular topic is usually grateful to find an appropriate text on that topic. Courses, modules, or case studies based on the molecular, multiscale, and systems organizing principles will similarly need resource materials. Ideally, the engineer should find these to be useful during university years and in later practice. We envision that texts will be written, but that the materials will include portable, web-distributed resources, as well.

3. Proposed Curricular Development

The proposed curriculum development is described following the layout in Figure 3. These are very abbreviated versions of proposed content developed by teams of chemical engineering faculty following the three planning workshops [see Appendix: Proposal Participant List].

3.1. Courses outside Chemical Engineering

Because of the heavy reliance of chemical engineering on science, particularly molecular sciences, creation of a new curriculum requires attention to supporting courses on which we depend. With the support of our partners in other disciplines, we must make the changes that re-establish the relevance of all those courses that we now hear our students say are “of no value”. No course required for this degree should be retained unless it has superior value. We are confident that we can ally the supporting sciences in a way that empowers students and increases their ability to know how to learn more when they need more. We believe we have an opportunity to utilize these supporting course hours to reinforce and provide important support for understanding the fundamentals behind the other segments described in this proposal. Four major opportunities exist here:

3.1.1. Biology as a Core Science for Chemical Engineering:

The ongoing revolution in the biological sciences is creating new challenges for chemical engineers in biotechnology, healthcare and the environment. Chemical engineers who are able to combine an intimate understanding of basic biological principles with the quintessential problem-solving skills of an engineer are poised to make large impacts in these arenas. To do this, chemical engineers must understand biological concepts that are relevant to – and can be harnessed for – engineering endeavors. Some of these concepts include: (1) *Specificity*. How do the specific interactions in biological systems give rise to properties seen notably in living systems, e.g., catalysis at low temperatures and pressures, active transport, and cooperativity? (2) *Regulation*. How do biological systems regulate chemical and physical processes, and how can this knowledge be used to control engineered biological systems? (3) *Evolution and information transfer*. How do biological systems evolve, and how can these mechanisms be harnessed to develop new biological systems with desirable properties? (4) *Sensing and signal transduction*. How do biological systems sense and transmit molecular signals, and how can this information be harnessed to develop sensitive and specific detectors? (5) *Energy generation and transduction*. How do biological systems generate and convert different forms of energy so efficiently (chemical, electrical, mechanical), and how can this knowledge be used for energy production and conservation efforts? In addition, chemical engineers must be familiar with the methods available to create, analyze and manipulate biological molecules and systems, so that their engineering toolkit is as complete and up-to-date as possible. Chemical engineers also must be familiar with the language used by biologists, and be comfortable operating in the biology culture, so that they can effectively translate breakthroughs in fundamental biological research to engineering applications in society. These educational objectives will the guiding principles for the supporting biology courses of the new curriculum.

3.1.2. Increased Emphasis on Material Science in Chemistry:

Exposure to the nature and properties of small numbers of molecules is essential to enable chemical engineers to contribute to the growth of nanoscience and technology applications. The fundamentals behind such work, including more emphasis upon quantum physics, single molecule actions, and the effects upon thermodynamic energy systems, can be accomplished by readjusting the components of chemistry and physics courses.

3.1.3. Integration of Ethics and Business Tools

In the particular case of Bio Ethics, we wish to develop good case study materials to empower each graduating student with at least one strong interactive experience on the issues and ramifications of decisions made in engineering work. We must also expose students to the communication channels of today and tomorrow. Information Science is an essential Business (and Engineering) tool.

3.1.4. Infusing Mathematics Elements with Relevant Examples i.e., "Learning by Doing"

We need to ensure that the relevant mathematics is taught in mathematics courses, and then that we reinforce these tools by relevant chemical engineering applications in our own courses.

3.2. Freshman Experience

Traditional chemical engineering curricula have not involved direct exposure of freshmen to their chosen discipline. The first course has come in the sophomore year, and is often a course in mass and energy balances. With new chemical engineering curricula we seek to produce sophomores who recognize the full breadth of opportunities that can be found in their chosen field of study, are excited about the prospect of enhancing their knowledge and skills through additional study, and are rightly confident of their ability to achieve tasks not possible prior to their freshman experience. An element in meeting these objectives is an experience that can be fulfilled through a specific course or accomplishment of a set of modules that is (1) exciting, substantive, and quantitative, (2) appropriate for the abilities of a large majority of freshmen entering the chemical engineering curriculum, and (3) adaptable to the local needs of universities having chemical engineering majors. Moreover, the content of such a course should provide students a quantitative (rather than merely descriptive) exposure to the fundamental tenets of modern chemical engineering, which are centered on molecular transformations, multi-scale analysis, and systems approaches.

3.2.1. Case Studies and Laboratory Modules

The case-study approach has been of great value in numerous disciplines, and we propose to develop case studies that can be incorporated into a laboratory or presented as stand-alone illustrations in a lecture-format setting. This will afford the maximum flexibility to the various departments to adopt them within their particular local constraints. The concept is to select examples with an easily grasped big picture and with details that can be appreciated and advanced by the students with a typical advanced high school background. The individual case studies will be selected so they embrace some, and possibly all, of the unifying themes – molecular transformations, multi-scale analysis, and systems.

Each case study is a module having the following elements: (1) a set of background reading suitable for students and, separately, background reading suitable for the instructor; (2) appropriate graphics and illustrations that can be incorporated into a lecture format and used for self-study by the student; (3) a discussion of the problem or set of problems to be addressed and its societal and economic impact, potential approaches to take in obtaining solutions, an outline of the concepts in engineering and science that may be essential in developing solutions; (4) one or several potential solutions with the trade-offs and implications of the approaches described; and (5) descriptions of recommended laboratory experiments that can be implemented easily to illustrate one or more aspects of the problem. The laboratory experiments are intended to be hands-on by the students and to the extent possible afford an open-ended component to the case study. The illustrations and graphics will take full advantage of the web-based tools for presentation and distribution. Finally, each module will show how the courses in subsequent years will provide the foundations in science and engineering that facilitate the development of complete solutions to the problem.

The following four examples are offered to illustrate the approach. We propose to develop a suite of at least ten modules. In addition to the four illustrations below, we have developed an extensive listing of additional topics and expected outcomes that might be covered in a lecture format; each of these could either stand on its own or it could be offered in parallel or link directly to the case study.

- *Desalination of Seawater.* The general area of water purification could be chosen as the centerpiece of a specific offering of a freshman chemical engineering course. The study could address scientific principles, societal needs, and economic realities by leading students from the broad topic (what is the extent of the problem; why is there a shortage of potable water in many regions of the world; and what are the consequences of this shortage, both with respect to health and geopolitics).
- *Sand to Silicon.* This case study embodies chemical and physical transformations and illustrates how chemical engineering can involve transforming natural raw materials into useful products.
- *Drug Delivery*. This case study embodies chemical and physical transformations, and illustrates how chemical engineering is involved in the design of medical therapies. It can show how one chooses a drug delivery strategy based on the chemical and physical properties of the drug, how the drug interacts with molecules and tissues in the human body, how the drug is transported through the body, and the medical need.
- *Crude Oil to Packing Peanuts (expandable polystyrene).* This case study embodies chemical and physical transformations, while simultaneously providing an overview of organic chemistry. It also shows how one chooses processes based on the reactivity of the reactants and the final desired structure.

3.3. Molecular Transformations

The abilities to analyze physical, chemical, and biological processes at a molecular level and to use this information to design new products and processes are hallmarks of modern chemical engineering. Chemical engineers are active in areas ranging from petrochemicals to microelectronics to biotechnology to the environment, and they bring a molecular viewpoint to the engineering challenges in all these arenas. Molecular topics are unfocused in the traditional undergraduate curriculum. By contrast, the molecular viewpoints of physics, chemistry, and biology will be **fundamental and ubiquitous** in the new curriculum. Throughout, students will learn how molecular structure relates to molecular behavior, e.g., reactivity, as well as material properties and other macroscale behavior. A key component of the curriculum will be the quantitative use of molecular modeling. The ability to predict properties and ranked comparisons has reached accuracies such that the chemical, pharmaceutical, and materials industries are adopting these methods as process and product development guides (Westmoreland *et al.*, 2002). Both predictive modeling and molecularly-based correlation provide important tools for chemical engineers.

- Molecular Basis of Thermodynamics (Sophomore). The traditional thermodynamics courses would evolve to add introductions to property correlations and ideal-gas heat capacities from statistical mechanics.
- New course in Molecularly Based Properties (Sophomore). Concepts of interaction energy, energetic and entropic properties related to binding mechanisms, substrate-enzyme docking and specificity, physisorption and chemisorption on supported catalysts, polymer structure, diffusion of gas molecules and relevance to other transport properties, selective ion-channel transport of ions, and vapor-liquid equilibrium. Appropriate theory and theory-based correlations will be introduced, such as gas-kinetic theory for transport, but reaction properties will not be included in this course.
- New course in Molecular Basis of Reaction Rates (Sophomore or Junior). Classification of reaction transition states as s/p-type or d-type leads to quantitative correlations of the corresponding rate constants. Transition-state theory, computational quantum chemistry, solvation effects, binding/reaction. Simulation methods would link molecular reactivity tangibly to system kinetics.
- Possible second or alternative new course in Molecularly Based Properties (Junior or Senior). More sophisticated theory and computation become possible. Transport properties, polymer/biomolecular conformations, mixture properties, molecular biology, and reactions. Special topics such as interfacial phenomena, nucleation/growth, mechanism-generation algorithms, and ADMET correlations.
- Modules for capstone design course (Senior). Process design and, increasingly, product design are used in senior capstone courses to link concepts to practice.

We propose to develop modules that include class content, example problems, instructor aids, student assessment, and module evaluation, similar to the NSF/CACHE-sponsored modules of Rowley et al. (2001). We will organize a multi-authored, multi-segment text to provide learning resources for the molecular properties courses, following the model of the NSF/CACHE-sponsored web text (Cummings *et al.*, 2001). Dissemination and assessment of the results will be aided by the ASEE Summer School for Chemical Engineering. This Summer School, held every five years, reaches over 200 chemical engineering faculty.

3.4. Multiscale Analysis in Chemical Engineering Education

The ability to analyze physical, chemical, and biological processes over a wide range of length and time scales, and to use the results in process design and control over a wide range of scales, underlies some of the top achievements in the history of chemical engineering. The importance of multiscale analysis has been implicit in the curriculum for many years. Still, advances in computational and measurement capabilities provide strong impetus for explicit multiscale pedagogy in chemical engineering. The advent of high-speed computing, from the prediction of molecular-level interactions at catalyst surfaces to process optimization and control of complex chemical and biological systems, provides powerful tools to the practicing engineer.

Multiscale analysis may be applied to materials and to processes or systems, as shown in Figure 4. On the vertical axis, materials vary in scale or complexity, while on the horizontal axis, process analysis varies in scale. Each block suggests examples of material for each year of the chemical engineering curriculum, and the arrows represent a possible path through the curriculum.

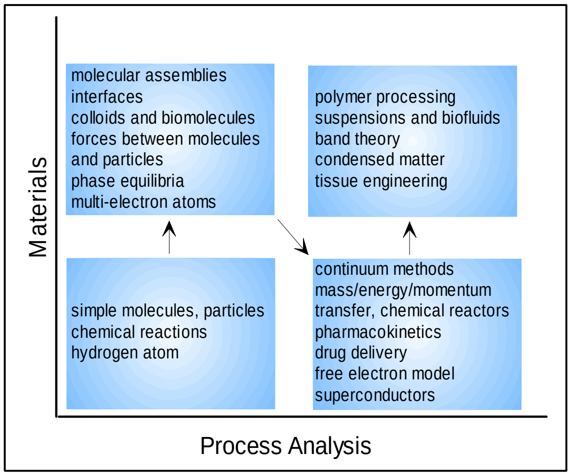

Figure 4. Application of multiscale analysis to

- Freshman year: multiscale analysis. Introduces the idea of scaling through simple dimensional analysis techniques that can be applied to a broad range of problems. We emphasize that dimensional analysis techniques require no knowledge of constitutive equations, thermodynamics, or other principles freshman have not yet been exposed to. The course would include mass balance principles.
- Sophomore year: mesoscale engineering principles. Classical colloid science along with contemporary nanotechnology. On the process side, chemical reactors and homogenous reactor engineering.
- Junior year: microscale engineering principles. Continuum-based description of mass, energy, and momentum transfer. Fluid flow with and without reaction, simultaneous heat and momentum transfer, interfacial transport, and catalytic reactors. New problems in pharmacokinetics, cell culture, staged operations, and separations processes. An “operation-scale analysis” course would feature operations from chromatography and cell sorting to petrochemical processes.
- Senior year: process-scale engineering principles. Continuum and molecular descriptions can be combined. Polymer solutions, polymer melts, particulate suspensions, biological tissues, and electronic materials fabrication. Multiscale concepts introduced throughout the curriculum can be reassembled and integrated in systems courses covering process and product design.

3.5. Systems Approach

The “systems approach” is a fundamental, integral concept that is not explicitly addressed elsewhere in the curriculum. The concept of analyzing a collection of components and processes as an overall system, rather than as individual components, is critical for frontier, as well as traditional, areas in chemical engineering. The systems component of the curriculum equips the graduate to:

- create and understand mathematical descriptions of physical phenomena,
- scale variables and perform order-of-magnitude analyses,
- structure and solve complex problems,
- manage large amounts of messy data, including missing data and information,
- resolve complex and sometimes contradictory issues of process design: sensitivity of solutions to assumptions, uncertainty in data, what-if questions, process optimization.

The systems component of the curriculum is the part that trains the students in the tools for synthesis, analysis, design, and manipulation of chemical and biological processes, units and collections thereof. The systems education teaches the students how to convert scientific facts and principles of chemical and biological systems into engineering decisions. The knowledge base of systems consists of methods for dynamic and steady-state simulation at multiple length and time scales, statistical analysis of data, sensitivity analysis, optimization, parameter estimation and system identification, design and analysis of feedback, methods for online monitoring and diagnosis, and methods for design of products and processes.

We propose to develop new educational materials that will enable instructors to integrate the systems concepts into the curriculum at each stage of the undergraduate educational program. This integration is a new and essential component of this proposal. As the students learn new scientific concepts, we propose to present in parallel the systems tools that enable specific scientific knowledge to be harnessed for engineering purposes. This purposeful and tight integration marks one significant change to the traditional curriculum. The changing scientific principles of interest, which include both newly emerging concepts in molecular biochemistry and cellular biology as well as the expanding tools of molecular modeling, require a concomitant change and expansion of the systems tools that we educate our students to use.

- Freshman year: systems overview. Plant-wide and product viewpoints, exposure to multi-faceted, real-world problems, degrees-of-freedom analysis, computer programming concepts, and simple applications.
- Sophomore year: engineering systems. Conservation laws for simple dynamic and steady-state systems, simple models for an experimental dynamic system (chemically reacting system), acquisition and analysis of noisy, complex, dynamic laboratory data, numerical simulation for simple models (single ODE), parameter estimation for simple models (one or two parameters estimated from one or two dynamic sensor measurements), equipment construction and sensor design
- Junior year: molecular systems: random variables, probability and statistics, stochastic systems and molecular level reactions as systems, stochastic kinetic models and Monte Carlo models, simulation as an enabling technology, optimization principles for design, parameter estimation, and decision making, general principles of experimental design for static and dynamic systems, use of models in predicting and understanding system behavior (analysis) and subsequent use of models in shaping system behavior (synthesis), systems biology: sequence to function: metabolic networks, gene expression networks, integrated gene-metabolic networks, examples from microelectronics, catalysis, systems biology.
- Senior year: systems integration and the marketplace: Multiscale systems, separation and resolution of time and length scales, design and analysis of feedback control systems, frequency response and analysis of spectroscopic data, monitoring and fault detection, energy and mass integration, design for environment and process efficiency, network targeting concepts, process operations: planning, scheduling, and the supply chain, the design experience: economics and business skills, safety, marketing, environmental impact, life cycle analysis, ethics, intellectual property, globalization, social and national needs.

A significant portion of the new teaching materials will be developed as case studies and modules that can be integrated into each year of the curriculum. Eventually new textbooks will be produced, but other forms of dissemination are also effective. For example, many modules currently under development in the systems area are distributed electronically and take advantage of computer simulation and JAVA applets to illustrate the concepts.

3.6. Laboratories

The laboratory experience is central to chemical engineering education: working with instrumentation that might be found in a modern workplace, testing laboratory results against well-defined theories, learning how to operate complex equipment (unit operations), and designing an experiment and building equipment for specific needs. Laboratories are also meant to teach other professional skills: communication, building and working with teams, handling real problems and data, and dealing with safety and environmental concerns. The opportunity presented by a new curriculum opens the possibility of comprehensively incorporating all of these dimensions and also breaking new ground in coupling the laboratory with the lecture courses.

Two main themes will be developed and implemented. These have overlapping goals, but each has unique dimensions. The first is an **integrated laboratory**; teams working in this laboratory will include students from all four years. The second theme will directly **update** the current **laboratory** experience by providing access to tools, equipment and processes that are generally difficult to maintain at the local level. A bonus of this approach is the ready access of demonstration experiments in lecture classes.

The integrative laboratory will be centered on student projects in process or product engineering involving both traditional and nontraditional chemical engineering projects, tailored to the industries hiring the graduates. Working in groups, students from all four years will spend up to one half of the year tackling a project. Work will be parceled out according to the skill set particular students can be expected to have, so that Freshmen and Sophomores might be expected to primarily undertake literature surveys and basic data gathering under the supervision of Juniors and Seniors. Over four years, students would have four different projects and would have worked in each with a different level of expertise. By having students in their early years of education work with more experienced students, it is anticipated that they will see how the knowledge that they will acquire in their junior and senior classes will allow them to analyze more complex problems. This will provide those students with engineering applications of their basic mathematics, chemistry, biology, and physics at an early stage of their educational careers.

The **updated laboratory** experience depends upon ubiquitous high speed video and data links that allow pooling resources across institutions and provide access to data from high quality equipment. As an example, individual universities develop equipment that can be accessed and controlled remotely, such as done in the MIT I-Lab (Colton, 2002). We propose to develop a procedure to permit access to such equipment by all universities in a “laboratory consortium”. A complementary approach is to work with companies to obtain access to data from on-going processes. The “laboratory consortium” would identify those companies that are operating processes for which they are willing to provide sufficient access so that students could undertake analyses of specific units or portions of processes. The advantage of this approach is that the equipment would be operating under actual process conditions. The disadvantage is that there would be no ability to undertake actual experiments.

Both approaches allow real experiments and data streams to be accessed during lectures. A third alternative is the development of virtual laboratories, modules that *simulate* real experiments. The advantage of this option is that once written, it is easy to implement widely.

The work to be undertaken will be in three principal areas:

- Develop "packages" for the integrative labs that can be widely used. These packages will likely be web pages that describe the project in detail and explicitly list how the teamork, communication skills, etc. could be implemented during the project.
- Develop and implement remote laboratory experiments.
- Develop and disseminate virtual laboratories.

4. Evaluation and Assessment

This section outlines the philosophy and general approach to assessment grounded in accepted learning theory and based on tested and validated instruments and methodologies. As individual instruction modules, lab experiences, and curriculum interventions are developed, we will design appropriate assessment measures guided by the principles outlined below. The breadth of this project provides a wealth of opportunities to understand how students learn chemical engineering and how intellectual development and curricular events are related.

Our framework uses triangulation whenever possible, using multiple metrics that are focused on general and specific educational goals and outcomes. Formative measures will measure ongoing program progress as we continually ask: how is it working? Results of these assessments will inform continuous program improvement. Summative measures are employed to evaluate end products and answer the question: how did it work? Our preference is toward performance-type assessments that directly measure students' ability to demonstrate specific defined outcomes. Performance assessments include exams, but can be creative team or individual experiences that are measured and judged by experts. Although indirect measures such as surveys and course evaluation forms may be used, they are de-emphasized in favor of direct measures. Such an approach yields more data on what students can actually do, and less information on what they tell you they think they can do. Longitudinal studies will track students' development within the curriculum and post graduation performance in industry and graduate school.

The project will employ a variety of qualitative and quantitative methods. Quantitative measures are most familiar to engineers and include things like exams, pre/post surveys, graded reports, and juried design competitions. Qualitative measures yield rich information about student learning and teaching effectiveness. These include open-ended questionnaires, interviews, video/audio taping and analysis, and other ethnographic methods. Qualitative tools are particularly effective for analyzing affective outcomes and higher order cognitive development.

Whenever possible we will employ control and experimental cohorts. This helps answer questions such as: Does the new curriculum yield a better "product" than the former, traditional curriculum? Control cohorts must be carefully defined to be demographically similar to any experimental cohorts, and we must strive to minimize extraneous variables. However, the nature of this project will not lend itself to universal application of the control group concept.

For example, if molecular engineering is taught to one group of students and not to another, then testing each for their knowledge of molecular engineering is unfair. Instead, one would want to give each cohort a problem whose solution is equally accessible regardless of curriculum. One then analyzes the students' solution approach and final product (using the appropriate qualitative methodology) probing for application of molecular concepts compared to other approaches. If students use molecular knowledge to produce a better solution, then the efficacy of the teaching approach is demonstrated. Such an assessment strategy requires close interaction of the curriculum designers with the evaluation specialists. In other cases, where no control cohort is possible, one must judge student learning against an absolute standard derived by consensus amongst the teaching team.

4.1. Overall Structure

An assessment team will be assembled early in the project. The team will include members of the various curriculum development teams, but will also include experts in assessment from fields such as education, developmental psychology, social science, and anthropology. Specific assessment plans will develop simultaneously with curriculum and module development. This allows application of the appropriate tools for each intervention. It requires an ongoing dialogue between the assessment team and the "teaching" teams. Concurrently, the assessment team will design measures that probe global outcomes (see below).

Our overall process will follow the outline below. Like any good assessment process, this is not necessarily linear. The path through this loop is not always continuous, but is adjusted as formative data are collected and analyzed.

1. <u>Define learning objectives and outcomes</u>. Each module or curriculum section will have many specific desired outcomes directly related to the curricular topics.
2. <u>Define specific abilities and desired performance criteria</u>. The performance criteria are particularly important since they are explicit and measurable descriptions of acceptable levels of learning.
3. <u>Identify appropriate, valid methodologies and instruments</u>. This process follows the framework described in this section.
4. <u>Establish a baseline</u>. Establishing some fairly specific knowledge about learning outcomes exhibited by the current chemical engineering student population will help inform our understanding of the new curriculum.
5. <u>Apply assessments to student products from new curriculum</u>. This involves conducting assessments, analyzing the various forms of data, and evaluating every aspect. It will take into account the evolutionary nature of implementation as modules, labs, and curricula are developed at different times and on different campuses.
6. <u>Feedback assessment results into the curriculum design loop</u>. Assessment results will judge the "product' but will also guide improvements in curriculum design and delivery.

4.2. Evaluation Summary

Although we are clearly interested in students learning fundamental technical knowledge, we are also interested in improving less quantifiable learning outcomes. These include the ability to think critically and work effectively with uncertainty; demonstrate effective teamwork and communication skills; improve self-confidence; understand global and societal interactions with engineering; employ safe environmentally friendly approaches; avoid segmented, compartmentalized learning; demonstrate the ability to handle real, complex, open-ended problems and data; demonstrate the ability to deal with complexity at an aggregated level; and to continue to learn beyond the classroom.

Demonstrating achievement of outcomes such as these requires a broad, multi-faceted approach to assessment. It requires a multidisciplinary team of engineers and experts from other fields. It requires an ongoing application process where results inform program improvement and student intellectual development is closely linked to curricular events. Our philosophy and framework will allow that to occur effectively and productively.

5. Dissemination

Annual workshops are planned at the end of each summer for sharing results among the development groups with the goals of sharing best practices, ensuring fit between components that are being constructed, and ensuring that the broad chemical engineering community is aware of the developments. Particularly in later years, we intend to hold workshops to teach faculty how to use the new curriculum materials and to offer help in designing a local curriculum and in deploying it.

6. Management

Vital to the success of this proposed discipline-wide curriculum reform is developing mechanisms for ensuring the continued, broad participation across the discipline. In addition it is important to ensure quality control of the materials developed and to provide for their wide dissemination.

A structure similar to an ERC will be put in place. The director of this Center for Chemical Engineering Education will rely on an Internal Advisory Board and an External Advisory Board for direction and quality assessment. The external advisory board will be composed of eight to ten leaders from the fields of chemical engineering, education, education assessment, and allied fields of science and engineering. They will meet annually to provide advice on progress, particularly quality of the work being done and how it compares with state-of-the-art practices.

The Internal Advisory Board consists of the Topic Leaders from the major topic areas address by the Center. These are the six areas: supporting courses, freshman experience, molecular transformations, multiscale analysis, systems approach, and laboratory experience described above plus evaluation and assessment. Note that these seven headings were written by teams chaired by faculty members from seven different universities. This broad representation is essential to the success of the effort.