PILLARS OF CHEMICAL ENGINEERING:
A BLOCK-SCHEDULED CURRICULUM

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Chemical engineering was once described by Lewis Norton as, "a general training in mechanical engineering . . . [with] their time [devoted to] applications of chemistry."[1] Within their short history, chemical engineers have moved from focusing on petroleum refining into such diverse fields as biotechnology, chip manufacture, specialty polymers, and nanotechnology.[2-5] It has long been commonplace for chemical engineers to ponder the future of the discipline[6-7] and most would agree that they have experienced two distinct paradigms[5-8]—a unit operations or process paradigm[9] (during the discipline's infancy) and a scientific fundamentals or continuum paradigm (some 40 years ago).[2-3] Today's engineering economy has shifted the focus once again, this time to product design/engineering[2,5,8] where we design/control macroscopic materials and processes through manipulation of their most fundamental units. This latest of shifts in research has yet to reach the undergraduate curriculum. To put it simply, the reform of undergraduate chemical engineering instruction is overdue and the curriculum has lagged behind research and industry.

While any number of reasons can be cited as the current cause of disconnect between chemical engineering research and teaching, perhaps the two most significant are:

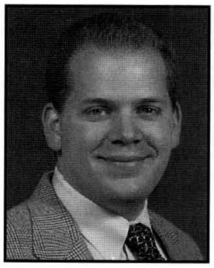
- Including emerging technologies in undergraduate education while at the same time increasing students' exposure to experimentation and design has put significant pressure on the number of credit hours taken by students in the traditional four-year engineering degree. A simple solution to the problem might be to allow the curriculum to grow organically and add courses wherever and whenever needed/desired, and to add a fifth (or sixth!) year to the curriculum. Students, in general, are opposed to this option, and despite numerous recommendations,[10,11] five year approaches have not been widely accepted (and may still fall short of the task).[12,13]
- The fear is very real that tailoring the curriculum to specialize in any specific emerging fields, while tempting, would likely cause chemical engineering to lose exactly the versatility that has made it possible to move into these fields in the first place.[3,14]

TOWARD A CONSENSUS

The challenge of developing a better chemical engineering curriculum, or indeed any engineering curriculum, is to build it in such a way that it prepares students for today's engineering economy, while enabling them (through a strong and well-integrated core of engineering knowledge) to maintain versatility through life-long learning and continuing education for tomorrow.

Prevailing wisdom from engineering educators, both in the US[10,12,15] and in Europe, is that the ideal engineering curriculum focuses on the following three issues:

- *Giving students a strong fundamental foundation by concentrating on the essential core of scientific and chemical engineering basics, including biological applications and molecular insight*[2-5]



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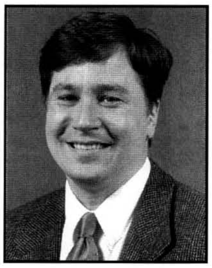

- *Enhancing systems thinking[16] by helping students integrate their knowledge across courses and disciplines[17] so they are better prepared to address open-ended problems*
- *Preparing and providing for continuing education and life-long learning[3]*

Specifically in chemical engineering, the shift in focus to product design/engineering [2,5,8] has inspired some to rethink the essence that sets the discipline apart and gives it the ability to accomplish these diverse tasks. It has been argued by many within the community that what makes chemical engineers unique is a focus on transformations (both chemical and biological, and of material, energy, or both) and multi-scale phenomena (from molecular to continuum to process).[16] Much of this is missing in the typical current curriculum, however.

The time is ripe for dramatic change in chemical engineering education, and there is consensus on what is needed in a revitalized future: molecular insight, systems/integrated thinking, and product as well as process design. What is needed, therefore, is a means of accomplishing these ideals.

A MODEL OF INTEGRATED IMPLEMENTATION: BLOCK SCHEDULING

The strong focus throughout engineering on establishing broad-based systems thinking within a discipline[7,8,9] has lead the National Science Foundation to fund a number of coalitions[19] that have championed the "integrated curriculum." In integrated freshman programs,[20-26] educators combine aspects of physics, chemistry, mathematics, etc., in order to more clearly show the interconnectedness and interplay displayed in basic engineering problems. Similarly, efforts have been directed at implementing complementary, integrated sophomore-level courses,[27,28] including a notable effort in chemical engineering at WPI.[29] In both programs, educators find that integration, while difficult to implement, can ultimately lead to better teaching and learning.[20]

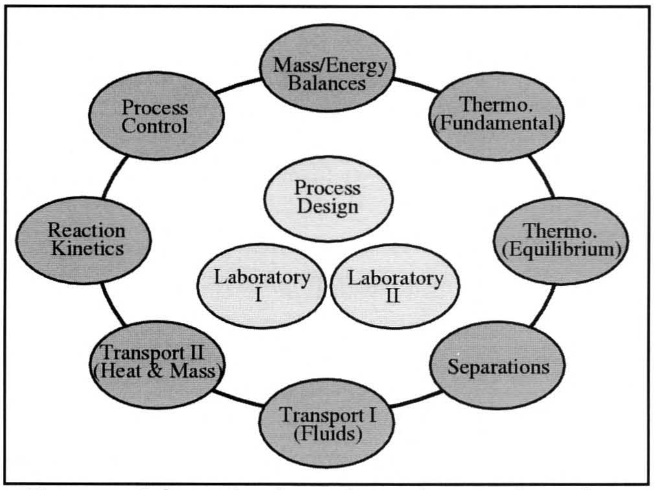

Figure 1. *Schematic of a traditional curriculum where content is confined to individual courses.*

In the upper levels of the curriculum, several integrated single courses have been recently developed that cover such specific subject matter as electromagnetic aspects of electrical engineering[30] and data acquisition and analysis,[31] for example. A few groups have even attempted to implement these types of changes in a discipline-specific,[32] subject-wide effort (examples include industrial,[33] civil,[34] and computer engineering[35]). One example of an integrated chemical engineering curriculum is a nontraditional, asynchronous, practice-oriented effort (PRIDE) attempted at West Virginia University in the 1970s[36] and continued in altered form (PRIDE II) through the 1990s.[37] While the curriculum discussed in the following sections shares many of the same goals as the PRIDE and PRIDE II programs, its ability to fit more easily into a traditional university structure, as well as its basis in previously validated pedagogy, make it significantly easier to implement in practice. It should be noted that the "blocks" discussed in the PRIDE program differ significantly in format from the block scheduling researched in K-12 education and discussed below. Ultimately, this scheduling plan was abandoned in PRIDE II.[37]

Building on these earlier efforts, a novel method to incorporate changes in topical material while at the same time fostering integration is to reform the undergraduate curriculum into a series of six "pillar" courses, using a successful pedagogical technique from K-12 education called "block scheduling."[38-40] In its simplest form, block scheduling involves transforming multi-semester courses into a single-semester course via extended, concentrated contact time. Among other things, the flexibility afforded by extended and more frequent contact time allows and encourages greater opportunity for active and collaborative learning.[40] Whereas time is lost in starting and ending both classes and courses in a traditional schedule, a block-scheduling format actually increases the total number of courses that can be offered[40] so that more elective courses are possible. Block-scheduling teachers are responsible for fewer classes; at the same time, the students have fewer concurrent courses. Therefore, both can focus more energy and effort on the course at hand so that, ultimately, both report less overall stress.[42]

Current engineering is often compartmentalized within a traditional 3-4 credit-per-course schedule, so that knowledge is disconnected and well-defined relationships are established only during the senior year, if at all (see Figure 1).[7] By moving to a block-scheduled curriculum, one can integrate complementary subject matter along with experiments and open-ended problems, so that students see the connections across the discipline during each course (see Figure 2). Also, by moving to this system, the pillar courses can have greater flexibility and therefore bridge to the length-scale that is (ironically) most often omitted in the undergraduate curriculum: the molecular-scale,[2] the microscale, or the nano-scale (depending on the topic/application). Ultimately, implementing block scheduling in a chemical engineering curriculum should allow

- *Students to gain systems insight through integration of their core knowledge*
- *The instructors to have the time to include truly multi-scale descriptions (from molecular to macroscopic scales) of chemical engineering content*
- *The instructors to have the flexibility to accommodate diverse learning styles*[39] *and incorporate active learning more effectively*[40]

A MULTI-SCALE APPROACH

Chemical engineers (during the unit operations paradigm) largely used macro-scale balance equations to perform analyses of interest. As the discipline moved into the continuum paradigm, chemical engineers shifted their focus somewhat and began to study systems at two distinct length-scales— the macro-scale and the continuum-scale. As continuum-level analysis in chemical engineering is of "higher order" (*i.e.*, requiring fewer assumptions and/or less averaging) than macro-balances of process units, the connection between these two approaches is fairly clear. In fact, it is a relatively simple matter to derive the corresponding macro-balances from a continuum analysis.

As chemical engineering moves into a new phase in its history, it is important to examine the inclusion of yet another scale of analysis[2]—the sub-continuum scale (alternatively micro, nano, or molecular, depending on the problem at hand.) Sub-continuum or "molecular" analysis relates to the continuum models in much the same way that continuum models relate to macro-balances. That is, molecular analysis can be used to derive many of the continuum properties of materials studied in traditional courses such as thermodynamics, transport phenomena, and kinetics.

Including the Sub-continuum approach, therefore, completes the picture in a way not previously possible in traditional chemical engineering courses.[16] The use of a block schedule yields sufficient time for an instructor to make full use of this multi-scale approach to ultimately convey to the students a stronger sense of the connectedness of chemical engineering knowledge. For example, in the transport phenomena pillar one can discuss the molecular origins of the thermal conductivity and calculate a theoretical value for a new material, use that conductivity to derive a continuum expression for the heat transfer coefficient into a flowing liquid, and then use that heat transfer coefficient in a macro-balance to establish design equations for a novel heat exchanger. This is but one example of intra-pillar synergy that is possible in the new curriculum.

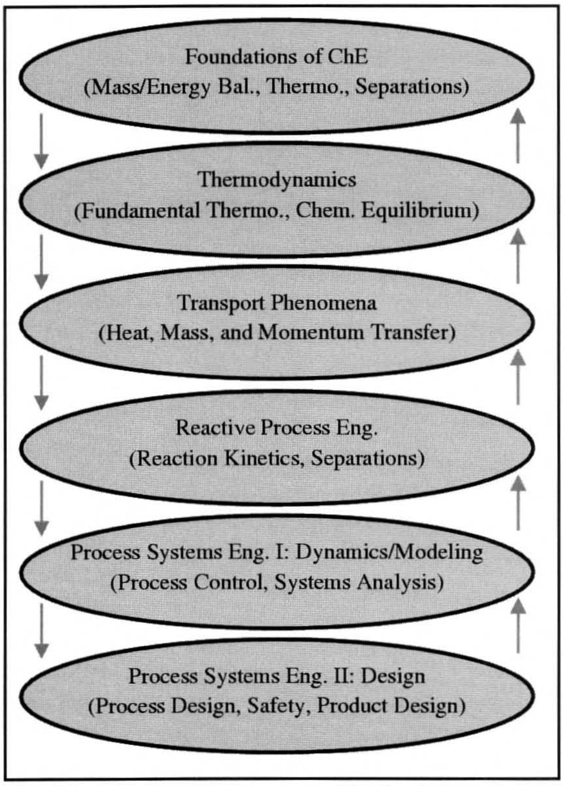

Figure 2. *Schematic of a block-scheduled chemical engineering curriculum. Here each individual pillar course contains tightly integrated topical information and the pillars are tied together through track-based examples/projects.*

THE PILLAR COURSES

The most significant change in moving to a block-scheduled curriculum lies in the shift from smaller, course-centered classes (classes designed with credit hour restrictions as the focus) to more comprehensive, topically-centered classes. These topic-centered pillar courses can range from five to seven credits, where most should include a one-credit experimental laboratory and in some cases a one-credit computational laboratory as well. The typical class might meet every day for one to two hours. The pillar course (plus labs) should be the only chemical engineering core course taken by students in a given semester, thus relieving the distraction of coordinating multiple chemical engineering workloads as well as allowing them to immerse themselves in the current topic. It should be noted that it is expected that moving to pillar courses will add few or no additional credit hours to a traditional curriculum, instead using those hours more effectively through restructuring.[41,42] In the remainder of this section we outline six potential pillar courses that cover, and expand on, the traditional content in chemical engineering.

■ *Foundations of Chemical Engineering*

In many current chemical engineering curricula, students face rudimentary thermodynamics first in the mass and energy balances class, then later (with more detailed material) in the (first) thermodynamics course, and even later in separations. While the repetition is undoubtedly helpful for students who may have struggled the first time or two they were exposed to rudimentary thermodynamics, remarkably few rec-

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ognize that things are being repeated. Surprisingly, this is true even when two thermodynamics courses are taught; in a course-centered, disjointed curriculum students have trouble seeing how the First and Second Laws of Thermodynamics relate to chemical equilibria and fugacity, respectively.

By switching to a block-based scheduling system, one can combine elements of mass and energy balances, thermodynamics, separations, and product design to form a pillar course on chemical engineering foundations. In this course, problem-solving techniques are introduced from both a (traditional) process-centric viewpoint and a product-centric viewpoint. The course will span from theoretical (basic thermodynamics) to applied (separations), allowing a simple route to problem-based learning of difficult theoretical concepts. The connections between balance equations, thermodynamics, simple phase equilibria, and separations can be easily conveyed as the material is interwoven throughout the course. The flexibility afforded by the extended contact time will allow lecture, problem sessions, and group study to form a portion of each class meeting so that students get constructive hands-on experience at every stage, including the use of process simulators (for process-centric problems) and molecular modeling tools (for product-centric problems). The experimental component (one credit) of the course will, as much as possible, differ by student group and represent each of the active elective "tracks" currently offered by the department so that students are continually exposed to varying fields of chemical engineering (polymers, process engineering, biotechnology, biomedical applications, etc.) and their relationship to the currently examined material. This course will be similar in many ways to the spiral curriculum used at WPI.[29,43,44]

■ *Thermodynamics*

This pillar course combines ideas from pure component thermodynamics (typically the first course) with multicomponent thermodynamics (typically in the second course). Additionally, it introduces molecular insight and use of commercial software (process and molecular simulators, such as Aspen, HySys, ChemCAD, Pro/II, Batch Plus, Superpro Designer, Accelrys, etc.) for solving complex problems. The main goal in this pillar is to provide students with the tools needed to solve realistic problems in phase and chemical equilibria. The course will have a strong focus on multi-scale analysis, for example, covering intermolecular potentials (molecular-scale) to aid students in choosing equations of state for novel materials (macro-scale.) The course will add a molecular description of entropy as well as vapor-liquid equilibrium (*i.e.*, gaining molecular insight into nonideal phase behavior). Extensive use of computational tools will allow time for the course to explore interfacial behavior, adsorption, and osmotic equilibrium.

■ *Transport Phenomena*

Combining the transport courses into a single pillar will greatly facilitate the study of analogies between the three modes of transport phenomena typically covered in chemical engineering curricula. Integration will allow coverage of the Reynolds and Colburn analogies in boundary-layer flow as well as direct comparison of linear transport relations, such as fluid drag and mass/heat convection. Removing the overlapping materials will allow the time to explore coupled heat, mass, and momentum transfer as might be important in problems ranging from traditional packed-bed reactors to microfluidics or microelectromechanical systems. Extensive use of commercial computational tools for equation solutions will also be included.

■ *Reactive Processes Pillar*

This pillar course will integrate reactor design, reaction kinetics, and advanced separation processes to allow comprehensive study of systems ranging from polymerization reactors to enzyme-catalzyed metabolism to (bio-)artificial organs. The course comprises topics from both the traditional kinetic and reactor design course as well as a small portion from the separations course. The material will integrate concepts from chemistry (kinetics, catalyst manufacturing), physics (transport, fluid flow), biochemistry/medicine (enzyme reactions, biomedical devices), and reactor engineering. Also, problems will bridge all length scales from the molecular level to the reactor level to the full-systems level (fuel cell with fuel reformer, gas separation, and heat-integration or microreactors.) As with the other pillars, both theory and experiment will be highlighted and detailed simulations will be included.

■ *Systems Engineering Sequence*

Traditionally, process control and process design are taught independently. It has been recognized, however, that within chemical engineering there is a significant interplay between process/product design, dynamics analysis, and control, as evidenced by a series of conference sessions (AIChE 1999-2003, FOCAPO/D meetings, etc.).[45-46] An integrated systems and design sequence will help students learn the fundamentals of dynamical modeling and analysis, control system design, optimization, and design engineering. Furthermore, the block-scheduling and laboratory time will allow for the incorporation of molecular insight and dynamic process simu-

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tion unit, showing typical condenser and reboiler arrangements and associated piping. Completion of the project placed little emphasis on the process aspects of the column, other than determination of the various stream temperatures. Students again worked in groups of 8.

Overall, this project has proved more successful in terms of achieving better student integration between the two cohorts. Neither group felt excluded from the project activities, and the completed reports exhibited clear signs of good cooperation. As is often the case with student assessment of group project work, some students were critical of the relatively loose nature of the problem specification and did not appreciate the fact that they had to struggle for some time to come to terms with what exactly was required of them. This criticism formed the basis of a subsequent lecture on project management and quality assurance aspects of design!

CONCLUSIONS

Working in a cross-disciplinary environment is an important part of the chemical engineering profession. Recognition of this fact has led to the development of a number of projects in the chemical engineering curriculum at the University College Dublin, which brings chemical engineering undergraduates (at third year/Junior level) together with chemistry and mechanical engineering students. Based on the experiences of a number of years, sample projects are presented that appear to offer good learning opportunities for each student group. We hope to further develop these projects in coming years to better integrate the project work with formal lecture classes, with the potential for joint lecture classes between each set of students.

Successful implementation of this type of endeavor inevitably depends on scheduling constraints and on the willingness and flexibility of the home departments of the students. Equally problematic are the differences in learning objectives for students in various departments, which clearly influence the choice of project. In the case of the chemical engineering undergraduate course discussed here, development of teamwork skills, along with a capacity to tackle loosely specified project assignments, are regarded as key learning outcomes.

Based on the experience to date, these cross-disciplinary projects are regarded as a successful addition to the chemical engineering curriculum at the University College Dublin. We anticipate that they will continue to be a part of the undergraduate program for several years to come.

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Block-Scheduled Curriculum

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lator software into the systems and dynamics pillar for the inclusion of industrial-style examples, as well as molecular effects on processes through changes in thermodynamic equations of state, etc. Also, optimization (a topic not generally covered in chemical engineering curricula), can be added to the curriculum. In the design course, process interactions between (feedback) control and design will be explored to demonstrate how changes in plant-operating state alter the difficulty of the controller design problem, thereby leading to design for control. Finally, product design will be introduced alongside of process design to highlight the similarities and differences that exist.

THE POTENTIAL FOR SUCCESS

The focus of chemical engineering, and indeed all of engineering, is changing. One needs only to scan the literature to find numerous references to "self-assembly," "nano-structured," "biomimetic," etc. All these topics are as foreign to the traditional chemical engineering curriculum as Beowulf, Jung, or (literally) Greek. The changing engineering landscape is quickly pushing chemical engineering into a third paradigm—the product design (molecular manipulation) paradigm. Without a shift in the curriculum, undergraduates will be wholly unprepared for what may well be their job in the near future. At the same time, even biomimetic or nano-structured materials need to be manufactured, likely in a plant; therefore, we clearly still need chemical engineers to fulfill traditional roles. The ideal new curriculum will balance these needs such that chemical engineering students maintain the versatility that they have enjoyed for years, while at the same time becoming more prepared for today's (and tomorrow's) marketplace. By integrating the core subject matter of the discipline into topic-centered pillar courses arranged in the curriculum according to block-scheduling principles, we can gain

- The *time* to connect theory to application and to integrate intradisciplinary ideas into rational constructions
- The *flexibility* to accommodate diverse learning styles in extended classroom experiences using well-integrated, active learning components and other modern teaching methods
- The *activation energy* to address emerging technologies and incorporate truly multi-scale analysis into the undergraduate curriculum

By integrating successful pedagogical techniques from K-12 education (block scheduling[38-40]) into the university environment and developing a block-scheduled curriculum in an engineering department, chemical engineers may build a model for all engineering disciplines.

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