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Renovating the undergraduate process control course

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Abstract

The undergraduate process control course and how it is taught is a controversial subject that generates lively discussions among control academicians, control practitioners, and chemical engineering faculty who do not teach control. Curriculum trends such as the new emphasis on biological engineering are influencing how process control is taught, and clearly there is difficulty in squeezing more content into an already full course. We discuss different academic and industrial viewpoints on the control course and suggest ways in which the control course can be renovated (a more positive image than "reformed"). The roles of simulation and laboratory experiments are highlighted, and alternative ways of teaching control in the future are described, including problem-based learning, case studies, and use of multimedia classrooms.
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1. Introduction

The discipline of chemical engineering is changing, as is evident from the addition of "bio", to department names such as "biomolecular" (e.g., Cornell, Illinois, Notre Dame, Pennsylvania), "biological" (e.g., Colorado, Northwestern, Rensselaer Polytechnic Institute, Wisconsin), and "biochemical" (e.g., Rutgers). These name changes indicate that more chemical engineering faculty are involved in research on biology-oriented topics and the percentage of chemical engineering undergraduates going to work for companies in the biotechnology and biomedical sectors has increased (AIChE, 2002–2003).

While chemical engineering graduates have been drawn into a broad range of new industries, the traditional base in the petrochemical industry has been undergoing dramatic changes. The industry is becoming increasingly global, and many companies and product lines have merged. Some chemical companies are morphing into life science companies and spinning off their chemical units; others are becoming virtual companies, outsourcing services (including research) that have traditionally been done in-house. Product cycles have dramatically shortened; time-to-market has become critical. Employees no longer expect life-time careers with a single company, rather graduate engineers can expect to have several different professional jobs during a career.

1.1. Drivers for change in chemical engineering education

There are two modes of chemical engineering practice today: maintaining the existing suite of major products through improvement of existing processes and creating new value chains through development and manufacture of new products. Chemical engineering education has historically focused on the first mode. The second mode, which requires that students be able to relate molecular processes to the systems scale of production, is only recently beginning to receive attention (Cussler, Savage, Middleburg, & Kind, 2002; NAE, 2004; NRC, 2003).

In addition to the traditional chemical processing and service (vendor) industries, graduates now work across a range of industries including biotechnology, pharmaceutical, elec-

tronics, advanced materials, and environmental. In response to this changing pattern, chemical engineering education programs have added new requirements or electives. This response has the potential to lead to a lack of coherence in addressing fundamental concepts and problem-solving skills, which are needed by students to work successfully across diverse industries during the course of their careers.

Today chemical engineering plays a central role among engineering disciplines because of its unique, historical focus on molecular transformations. In recent years many newer industries have come to appreciate the need for process engineering and have realized the potential benefits of combining molecular engineering with multiscale analysis and process systems design. This leads naturally to an unusually broad range of interactions between chemical engineering and nearly all other engineering and science disciplines.

Curriculum reform must address the increasingly foundational role of biology in addition to chemistry and physics in traditional industries and the need to prepare students for versatile, multifaceted careers. Process control, and more broadly systems engineering, are key elements in the renovation of the chemical engineering curriculum.

1.2. Frontiers of chemical engineering education workshops

Since 2003, four NSF-funded workshops have been held to assess the chemical engineering curriculum. Faculty from more than 50 universities and industry representatives from 15 companies reached strong consensus that there is a case for restructuring the curriculum while retaining the important attributes and skills of chemical engineering graduates. See MIT (2006) for full proceedings from these workshops. Key drivers for curriculum reform are addressing the increasingly central role of biology in the traditional industries that hire chemical engineers and the need to prepare students for versatile, multifaceted careers.

Workshop participants defined three organizing principles of an undergraduate chemical engineering education under the general headings of molecular transformation, multiscale analysis, and the systems viewpoint. 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 transformation is a unified treatment of phenomena at this level. Second, chemical engineers are effective because they combine macroscopic engineering tools with molecular understanding. Multiscale analysis covers the tools appropriate to a given length or time scale (molecular dynamics, continuum equations, macroscopic averages). It also provides an appreciation for the ways in which phenomena occur at different scales (e.g., ranging from kinetic mechanism to heat duty in a packed-bed reactor), an understanding of how molecular structure affects macroscopic properties, and the connection between transient and steady state processes. Third, realistic chemical engineering problems feature multiple interacting components and draw important information from fields outside chemical engineering. The analysis of such problems depends on the

mastery of a variety of tools. Systems analysis and synthesis constitute the organizing principles that enable the manipulation of processes to achieve the desired behavior or performance. The chemical engineer leverages knowledge of molecular processes across multiple length and time scales to synthesize and manipulate complex systems that encompass both processes and products. Efforts are underway to revise the curriculum using these three organizing principles (MIT, 2006).

1.3. Focus of this paper

Given this milieu of change and reassessment of the chemical engineering curriculum, we focus on the undergraduate process control course because process control is the subject of the CPC7 conference. First, it is important to recognize that, as indicated above, process control is one building block in the systems area of chemical engineering, which includes courses such as modeling, simulation, optimization, and statistics. Most chemical engineering departments in the U.S. typically teach two or three of these courses, although some may be electives. So clearly process control course content is impacted by content of other courses taught in a given department. Second, all of the authors of this paper reside in the U.S., so the discussion below is influenced by that country's educational and research environment (such as the pressures of engineering accreditation in the U.S.). However, we believe many of the educational issues raised are of interest outside the U.S. To propose a "one-size fits all" educational approach in the process control course does not recognize the diversity of chemical and biological engineering programs, hence our objective here is to offer different opinions and set the stage for future discussions.

In writing this paper, all five authors subscribe to the following principle: we believe that B.S. chemical engineering graduates are improperly served if upon graduation they have no knowledge of how to operate equipment they design, how to control processes, or understand the dynamic nature of how a process behaves. How a specific department wants to deliver this knowledge is certainly a topic for debate. In the sections below we frame this debate by addressing the following questions: (1) what control concepts are most important; (2) what is the industrial view of control education; (3) what is the possible influence of biology on the control course; (4) should there be more emphasis on batch control; (5) what topics could be removed or de-emphasized in the typical control course; (6) what is the balance of simulation versus experiments in control education; (7) what can be gained from a case study approach in control education; and finally (8) how might the future process control course change from its current emphasis?

2. The case for curriculum reform involving systems

One of the major undercurrents of curriculum reform is to determine what role biological science and engineering will play in the future curriculum. A corollary to this question was if new courses are added to the curriculum, what can be removed? Clearly all departments face a variety of local constraints that result in relatively inflexible paths to the degree (with a hard con-

straint on the total number of credit hours . . . a zero-sum game). At some point it becomes necessary to carry out a major restructuring of the curriculum in order to satisfy all of the goals of the chemical engineering degree. Therefore it is valuable to step back and take a more holistic view of the chemical engineering degree.

2.1. Desirable attributes of graduates

Engineers are fundamentally problem solvers, seeking to achieve some objective of design or performance in the face of 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 the aim is to equip graduates to grasp fundamentals and engineering tools, enabling them to specialize or diversify as opportunity and initiative allow. Based on discussions about desirable professional attributes (MIT, 2006), a chemical engineering education should enable graduates to:

(1) Make estimates and assumptions, face open-ended problems, deal with noisy data and uncertainty, and envision possible solutions.
(2) Enhance their problem-solving skills; use computational tools; perform economic analysis; and plan, execute, and interpret experiments.
(3) Integrate knowledge and information to aid in solution of chemical engineering problems.

Note that there is a strong thread of systems engineering in these attributes. These principles are similar to those recognized by researchers in problem-solving methodologies, e.g., Woods (1994).

2.2. The systems approach in the curriculum

The systems component of the chemical engineering curriculum ensures that chemical engineering graduates should be able to create and understand mathematical descriptions of physical phenomena; scale variables and perform order-of-magnitude analysis; structure and solve complex problems; manage large amounts of messy data, including missing data and information; and resolve complex and sometimes contradictory issues of process design. Graduates should be able to handle sensitivity of solutions to assumptions, uncertainty in data, what if questions, and process optimization. The systems approach is a fundamental concept that is explicitly addressed only in a few chemical engineering courses. The concept of analyzing a collection of components and processes as an overall system, rather than as individual components, is critical for frontier areas of chemical and biological engineering, as well as for traditional areas.

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, online monitoring and diagnosis design and analysis of feedback systems and design of products and processes. 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 currently used. A proposed set of systems topics covered during each of 4 years of the curriculum has been presented by Edgar and Rawlings (2004).

2.3. Differing views of the process control course

Not all faculty share the view that the systems approach such as taught in the process control course is a critical component in chemical engineering education. At the first Frontiers Workshop in January 2003, participants were asked to identify non-critical parts of the curriculum. Different groups reported a long and varied list of proposed changes to the curriculum, but notably a few groups reported that the subject of process control was high on the "hit list" to be removed from the curriculum. While process control was not the only option for elimination, it was disconcerting to see it in such an egregious position. Apparently the value of process control to academic chemical engineers is not as high as many in the control community believe it should be.

This was not the first salvo fired at the value of process control in the curriculum. In a look at the future of chemical engineering education, Cussler et al. (2002) declared that a number of fields like thermodynamics, reaction engineering, transport, and control can be relegated to the scrap heap of "mature technologies" that will not have much future impact in the discovery of new technology. They proposed dropping courses on control and optimization but added several disclaimers: "First, we accept without question the importance of process optimization to commodity chemicals. Secondly, we recognize that process control has a key role in ensuring the success of those other cornerstones of competitive advantage in specialty product manufacture; safety, consistency and quality. Our third hesitation stems from our unwillingness to sacrifice any of our technical core to less-quantitative business ideas. Still, we recognize that a large part of our future is going to be in areas where different skills are needed". This article has sparked spirited discussions in many departments considering curriculum change.

So why does the process control course cause fear and loathing among non-control faculty? Like design, it is usually taught by a small subset of faculty, as opposed to thermo, transport, etc. With the emphasis today on "bio, nano, enviro, and info" at funding agencies such as NSF, NIH, and DOD, it is not clear where process control researchers (and thus instructors) fit into this agenda. Hiring faculty at research-oriented departments has certainly moved in the same direction as the available funding (which includes the disproportionate effect of the Whitaker Foundation in the bio area). Faculty in these areas are oriented towards discovery-type research, far from the details of making commercial quantities of products. Some of these faculties are now being asked to teach undergraduate process control, which can represent a major shift from their normal teaching assignments. In fact, we estimate that less than 40% of undergraduate control courses in the U.S. are taught by someone for whom pro-

cess modeling and control is a primary research focus. However, engineers from industry view the reduced emphasis on process control due to the fact the "no one wants to teach it" as a weak argument.

Another strike against academic process control as a relevant part of the curriculum was the article published by long time practitioner Shinskey (2002) (retired from Foxboro). He stated there has been little or no progress in 35 years in closing the industrial–academic gap in process control, causing B.S. graduates to be unprepared for industrial assignments. This is reminiscent of statements heard at technical meetings 30 years ago that "control research is dead or at best irrelevant". Obviously it rose from the ashes in the late 1970s and has been alive and well for the past 25 years. It is interesting that Shinskey and Cussler express opposing views. Shinskey argues that nothing important has been accomplished, whereas Cussler states that so much has been accomplished there are no major improvements expected in the future. To use an analogy articulated by Tom Badgwell, "Shinskey says we have been driving in the wrong direction (but we can turn the car around), while Cussler says the car is out of gas and drivers are no longer needed".

Fortunately it was concluded in subsequent Frontiers workshops that a systems viewpoint is very important for chemical engineers and separates them from chemists, biologists, and other engineers. Unsteady state behavior, mathematical models, and feedback control are important concepts in living systems, because any organism at steady state is dead. Industrial chemical engineers at the Frontiers Workshops seem to have little doubt that process control is important to keeping modern chemical plants operating. A high percentage of current job advertisements for experienced chemical engineers involve skills in computer control and operations. So that seems to bode (no pun intended) well for keeping process control in the curriculum. While it is true that a little bit of process control could be inserted in five or six chemical engineering core courses in the name of a pervasive systems approach, that approach may not be effective and could be easily diminished in any course by individual faculty option due to "lack of time". Because process control is one of the few "integration" courses in the curriculum, keeping it as a separate course appears desirable, as well as strengthening the systems content in other core courses.

3. Content of the process control course

New criteria for chemical, biochemical, biomolecular and similarly named engineering programs have been proposed in 2005 and are under review by the AIChE Education and Accreditation Committee, Chemical Engineering department chairs, and ABET (Accreditation Board for Engineering and Technology). The proposed criteria state that graduates must have:

- thorough grounding in the basic sciences including chemistry, physics and biology, appropriate to the objectives of the program, and
- sufficient knowledge in the application of these basic sciences to enable graduates to *design*, *analyze*, and *control* complex physical, chemical and biological processes, as appropriate to the objectives of the program.

While the central role of process control is stated in the second bullet, it does not ensure or require that a complete course on process control be taught (this can be influenced by program objectives stated for a given department).

3.1. Elements of a traditional control course

Topics covered in a typical 15 week undergraduate process control course include dynamic behavior (with 1 week on Laplace transforms and analytical solutions to ODEs), physical and empirical modeling, computer simulation, measurement and control hardware technology, basic feedback and feedforward control concepts, and advanced control strategies. Many of these topics can be presented in a way that reflects applications in biochemical or materials engineering although the course is certainly traditional in its coverage. Table 1 states the knowledge, abilities, and skills (KAS) a student should gain from a typical process control course. Because engineering accreditation now encourages outcomes for each course to be formulated, every process control course taught in the U.S. has a KAS list that is provided to the students taking the courses.

As part of an NSF-funded "Department Level Reform" project, Table 2 shows the results of a ranking of process control concepts by faculty at various U.S. universities who teach process control. The "Pillars of Chemical Engineering" research project (McCarthy & Parker, 2004) has studied core subjects

Table 1
Knowledge, abilities and skills for the process dynamics and control course

Upon successful completion of the course, students should be able to
1. Develop mathematical and transfer function models for dynamic processes
2. Analyze process stability and dynamic responses
3. Empirically determine process dynamics for step response data
4. Understand different types of feedback controllers
5. Analyze and tune PID controllers to desired performance
6. Read process and instrumentation diagrams and translate to block diagrams
7. Perform frequency domain analysis of linear dynamic processes
8. Design feedforward control, cascade control and time-delay compensation
9. Analyze multivariable process interactions
10. Define a process control problem, based on a flowsheet, in terms of objectives, manipulated variables, controlled variables, and constraints

Table 2
Ranking of process control concepts (University of Pittsburgh NSF Grant, McCarthy & Parker, 2004)

Concept	Understanding (1–10)	Importance (1–10)
Qualitative aspects, e.g., cause and effect relationships	5.0	8.0
Time domain concepts	5.0	6.5
Dynamic behavior-simple models, e.g., CSTR, dead time, plug flow; creating transfer functions from unit operations	6.0	8.0
Origin and magnitude of system perturbations	4.0	7.0
Linear state-space models and formulation, and applied linear algebra	4.5	7.0
Using experimental data in process analysis and design	5.0	8.0
Dynamic behavior—open and closed-loop responses	7.0	8.0
Feedback, control-analysis, purpose	6.5	8.0
Design methods for single input/output systems	6.0	7.0
Difference between performance and design problems; process/controller design vs. process/controller synthesis	5.0	7.0
Frequency response of a linear system, Laplace techniques	5.0	6.0
Stability analysis (bode diagram, root locus)	6.0	7.0
How relative gain array can predict multivariable/multi-loop control difficulties for optimization	5.0	6.0
Effects of process dynamics and control on process design decisions	5.0	8.0
More advanced control synthesis methods (e.g., MPC) for complex multivariable systems	3.5	5.0

in chemical engineering, and Table 2 shows 15 key concepts identified by a poll of selected instructors from the U.S. that are specifically related to the process control course, out of 30 total in the systems area (design, control, optimization, etc.).

The relative rankings in Table 2 are perhaps not surprising because they represent how faculty have taught the course in the past. The second column indicates the level of confidence (rated from 1 to 10, with 10 the highest) that the students understand the concept by the end of the course, and the third column estimates the importance of learning the concept for practicing engineers. Both of these scores are based on the opinions of those instructors surveyed.

Relevant to this assessment are comments from engineers at Eastman Chemical about the importance of certain topics taught in process control. While the need for a B.S. graduate to understand Laplace transforms, frequency domain analysis, or relative gain arrays may not appear to be widely applicable, the knowledge of how to control processes using measurement feedback is applicable to most every job a young graduate may encounter and should be considered a basic building block of their education. The new engineer should also understand that process control is a natural extension of material and energy balances, that is, dynamic loops are used to keep the material and energy balances in balance. Nearly all graduates going into manufacturing jobs should be exposed to the need to know more about the basics of process control. The practical aspects of process control such as understanding control objectives, how a control strategy fulfills these objectives, how to tune control loops, and understanding dynamic interactions among process variables are often currently learned on the job. The disturbing fact is that many recent graduates feel shortchanged when they learn how critical process control is to their job effectiveness and how little they understand about it from their undergraduate education.

To further illuminate the skills and concepts that industrial employers find important in a chemical engineering graduate, one of the authors (K. Muske) conducted a survey of 34 industrial practitioners working in the systems and control area who represent the biotechnology, pharmaceutical, petroleum and petrochemical, chemical, consumer product, and process control consulting business areas. Each of these individuals was asked to rank a list of 10 skills and concepts in order of importance, with 10 being the most important and 1 being the least important. Thus each survey respondent had to make a decision on the relative importance of each skill. The results of this survey are presented below, with the average ranking shown in parentheses:

(1) optimization of a process or operation (8.6);
(2) statistical analysis of data and design of experiments (7.2);
(3) physical dynamic process models (7.0);
(4) statistical/empirical dynamic process models (6.9);
(5) multivariable interactions and multivariable system analysis (6.6);
(6) statistical process control and process monitoring (5.3);
(7) design and tuning of PID loops (5.1);
(8) nonlinear dynamics and analysis of nonlinear systems (3.9);
(9) frequency domain analysis (2.4);
(10) expert systems and artificial intelligence (1.9).

First it is noteworthy that five of the top six skills are not necessarily taught in many process control courses, which perhaps reinforces the need for students to have a systems education rather than just a control education. Dynamic process modeling skills are clearly important to these industrial practitioners. The average ranking for physical modeling is 7.0 and the average for empirical modeling is 6.9. These results suggest that process identification may be a skill that should be emphasized in the process control course along with physical dynamic modeling. PID loop tuning and design gave a bimodal distribution, causing a lower than expected ranking. Respondents from the more mature industries and consultants ranked this skill very highly, while respondents from the biotechnology and pharmaceutical industries ranked it rather low. Process optimization received the highest average rank of 8.6. This skill is clearly valued in a cross-section of industries, however, it is not typically cov-

Table 3
Proposed structure for a biologically oriented dynamics and control course (Parker et al., 2004) (number of lectures in parentheses)

Topics
Dynamic modeling (4)
Principles of fundamental modeling; chemical and **biological process examples**; introduction to empirical modeling
Linear and nonlinear systems analysis (7)
Matrix algebra and linear state-space systems; linear systems theory; introduction to nonlinear systems theory; dynamic simulation; chemical and **biological process examples**; introduction to the Laplace transform
Feedback systems (7)
Basis principles of feedback; **physiological control systems; homeostasis as a setpoint-free feedback system; feedback in biochemical reaction networks**; closed-loop response analysis; servo vs. load behavior; feedback control of chemical process systems; **closed-loop drug delivery**
Feedback control synthesis (8)
Basic principles of model-based controller design; PID controller design & tuning; advanced single-variable control techniques; multivariable control techniques; *model predictive control*; chemical and **biological process examples**
Advanced topics (4)
Large-scale systems and plant-wide control; parameter estimation and experimental design; *state estimation*; **introduction to systems biology**

ered in process control courses. More integration of this topic into the curriculum appears to be warranted. There is a clear preference for coverage of multivariable systems as opposed to nonlinear analysis. While multivariable analysis and loop pairing are presented in most texts, it is unclear how many instructors actually have time to cover this topic in a one semester course. Frequency response received the second lowest average ranking at 2.4, so it is not perceived as directly relevant to industrial practice. The high rankings for statistical analysis of data and statistical process control and monitoring appear to indicate that some integration and reinforcement of statistical analysis in the process control course would be appropriate. However, the statistical process control and monitoring rankings were bimodal with respondents from the more mature industries ranking this skill lower than respondents from the biotechnology and pharmaceutical industries. Finally expert systems received the lowest average ranking.

3.2. Incorporation of biological content in process control courses

The dynamics and control course could include examples of biological systems along with chemical process applications. Due to their inherent complexity, biological systems offer a rich set of dynamic problems that chemical engineers can analyze or simulate. A recent paper by Parker, Doyle, and Henson (2004, 2006) reviews three departments where process control and related courses have adopted a strong emphasis on biological systems: UC Santa Barbara (Frank Doyle), University of Massachusetts (Mike Henson), and University of Pittsburgh (Bob Parker). A general composite structure for a semester-long system dynamics and control course is illustrated by the syllabus in Table 3. Bold entries represent new topics specific to biological systems. Italicized entries are theoretical topics often considered optional in a traditional control course but which are viewed as important for a biologically oriented course. Because biological systems are often high order, multivariable, and highly nonlinear, which may preclude Laplace transform-based analysis, the introduction of state-space models and associated analysis tools is essential. Because students often retain little of the mathe-

matics presumably learned in their lower level courses, a few lectures on matrix algebra and linear state-space systems are required to review core material and to ensure that students with deficient backgrounds understand the basic concepts. Feedback is a concept easily introduced in the context of biological system examples.

The process control course at the University of Massachusetts (http://www.ecs.umass.edu/che/che446) previously focused on Laplace transform analysis and chemical process applications. In 2003 biological systems were chosen as an appropriate vehicle for changing the course content. The first few weeks cover fundamental modeling because undergraduate students typically have little experience formulating dynamic balance equations. A case study approach with traditional chemical process examples and biochemical system examples (e.g., yeast metabolism) is utilized. A continuous yeast fermentor model is introduced and revisited in lectures and homeworks throughout the semester. Both time domain and Laplace domain analysis techniques receive extensive coverage. An introduction to matrix algebra is necessary because this material is not covered in the required mathematics courses. Using linear state-space models, closed-loop stability is analyzed in both the time and Laplace domains. While most of the material on single-loop controller synthesis is traditional, introduction to time domain controller design techniques is provided in parallel with the Laplace domain methods. The analysis and design of multivariable control systems are covered in the final few weeks. Here the main emphasis is linear model predictive control because many students entering the refining, petrochemical, and chemical industries will encounter this technology. The continuous yeast fermentor model is used to illustrate the controller design techniques introduced throughout the course.

Traditional control topics that receive reduced coverage compared to the previous University of Massachusetts course include transfer function models, Laplace domain analysis and design techniques, advanced single-loop control, frequency domain analysis, and controller design techniques. While these topics are admittedly valuable, a broader view of dynamic systems and feedback control was deemed to be more important given current trends in the chemical engineering profession.

The biology component in the dynamics and control course (ChE 1034) at the University of Pittsburgh emphasizes the analysis and control of biomedical systems at the whole-organism level. Half of the course is devoted to modeling, ranging from fundamental to empirical approaches in both continuous and sampled-data (discrete) domains. The students are taught how pharmacokinetics (the time profile of a drug) is distinguished from pharmacodynamics (the disease dynamics, effect of the drug on the disease, and toxicity), in much the same way valve dynamics and process output response are captured by separate blocks in a block diagram. One modeling problem covered is the insulin-dependent diabetic patient (Parker, Ward, Peppas, & Doyle, 2000). The remainder of the course focuses on the model-based synthesis and analysis of classical and advanced control systems.

At UCSB, a new course was offered in the Spring, 2004 quarter, entitled "Engineering Approaches to Systems Biology". The course is taught at a dual-level (seniors and new graduate students) (Parker et al., 2004). The balance of topics in the course is approximately one third on basic cellular regulation, one third on applications of systems engineering tools to biological problems, and one third on detailed case studies to illustrate current methodologies and future challenges. Advances in molecular biology over the past decade have made it possible to examine the causal relationships between microbiological processes initiated by individual molecules within a cell, and their macroscopic phenotypic effects on cells and organisms (Kitano, 2002). This perspective provides increasingly detailed insights into the underlying networks, circuits, and pathways responsible for the basic functionality and robustness of biological systems. Model development involves translating identified biological processes into coupled dynamical equations that are amenable to numerical simulation and analysis. These equations describe the interactions between various constituents and the environment, and involve multiple feedback loops, responsible for system regulation, and noise attenuation and amplification. Stephanopoulos, Solis, and Stephanopoulos (2005) have recently proposed a process systems engineering framework for nanoscale processes with a strong emphasis on biological systems. Evidence of the rapid growth of this area is the first chemical engineering research conference on systems biology, which was held in 2005 (http://www.fosbe.org) and had over 160 participants.

3.3. Development of non-traditional examples

Given the recent emphasis on biology in the curriculum, it is pertinent to review available textbooks in different core subjects which at least acknowledge this area of application. Three process control textbooks contain a number of examples and exercises illustrating applications of process control to biological engineering:

(1) Ogunnaike and Ray (1994): drug delivery, blood pressure control, bioreactors.
(2) Bequette (2003): biochemical reactor, pharmacokinetic models, drug delivery, blood glucose control, blood pressure control.

(3) Seborg, Edgar, and Mellichamp (2004): fed-batch bioreactor, drug delivery.

Of course changing and updating textbook material has rather long time constants, usually greater than 2 years, but new supplemental curriculum materials can be developed more quickly to augment existing textbooks.

Faculty in process dynamics and control can contribute to the development of instructional materials in new areas such as bio and nano in a variety of ways. The construction of case studies for different applications would ease the burden on non-experts to incorporate novel examples into the curriculum. Software tools such as the Process Control Modules (Doyle, Parker, & Gatzke, 2000), Java-based Control Modules (Yang & Lee, 2002), and Control Station (http://www.controlstation.com) are well-suited for introducing traditional concepts and applications. However, new software tools are needed to increase the exposure of chemical engineering undergraduates to biological complexity and to allow the application of the theoretical concepts introduced in the course to representative biological systems. Ongoing efforts, such as those organized by the CACHE Biosystems Task Force, are focused on the development and refinement of biologically relevant systems courses. This group is currently working on course revisions as well as software module design as a means to integrate biological content throughout the chemical engineering curriculum. More details are available at http://www.cache.org.

3.4. Batch versus continuous processing emphasis

Batch processing is widely used to manufacture specialty chemicals, metals, electronic materials, ceramics, polymers, food and agricultural materials, biochemicals and pharmaceuticals, multiphase materials/blends, coatings, and composites—an extremely broad range of processes and products. Batch process control is a topic that requires a different approach from continuous processing and is probably under-emphasized in the undergraduate curriculum as well as the process control course. A few departments such as University of Washington (Larry Ricker) cover batch processing in a second elective control course.

In order to provide an introduction to batch process operations, control content can intersect with process design/operations, process control, process safety, and reaction engineering. Batch operational practices and control system design differ markedly from continuous plants. Batch control systems operate at various levels:

- batch sequencing and logic control;
- control during the batch;
- run-to-run control;
- batch production management scheduling.

A batch processing theme in the control course would emphasize different topics than normally covered. Discrete logic is needed for the control steps and for safety interlocks to protect personnel, equipment, and the environment from unsafe condi-

tions. Control during the batch requires treatment of nonlinear fundamental models because there is no steady state that can be used for linearization. Run-to-run (or batch-to-batch) control can be employed when recipe modifications are made from one run to the next, which is common in specialty chemicals and semiconductor manufacture. Typical examples are modifying the reaction time, feed stoichiometry, or reactor temperature. Such modifications are done at the beginning of a run (rather than during a run). Finally batch scheduling brings in principles of optimization with both continuous and integer variables.

3.5. Reducing the emphasis on Laplace transforms, frequency response, and controller tuning

In light of current curriculum trends that are adding new topics to process control and other courses, coverage of topics such as Laplace transforms, analytical solutions to linear differential equations, linear algebra, frequency response, and multiple methods to tune a PID controller probably needs to change. Computer simulation should take a more prominent position compared to theoretical analysis. The availability of computer-based tools such as Simulink in MATLAB or Control Station permits new pedagogical approaches for teaching process control.

The teaching of Laplace transforms has historically been viewed as a major part of the process control course, because the concept of the transfer function is very important. Prior to 1990, the dependence on Laplace transforms arose out of necessity because easy-to-use computational and graphic tools were not available. Rigorous analysis was necessary to obtain transient responses. While there is a need to understand analytical responses for simple dynamic systems, Laplace transform analysis is of marginal utility for analytically deriving closed-loop behavior of complex systems, especially when time delays exist in the process. One analog in separations is the use of McCabe-Thiele diagrams to gain understanding of staged distillation; however, to solve realistic problems, it is preferable to carry out tray-to-tray calculations using readily available software. Reducing the current course effort on linear systems analysis will rely on using interactive software such as MATLAB Simulink.

It will still be necessary to teach students s-transforms in order to use MATLAB Simulink for simulation of closed-loop diagrams. Students find the drag and drop approach for constructing feedback control systems a welcome alternative to writing m-files to perform closed-loop simulation. Some faculty feel that frequency domain material is difficult for most students to understand and apply. Therefore in spite of the clarity afforded by frequency response in performing analysis such as controller robustness, some reduced emphasis on this aspect seems to be warranted.

At CPC5 Ramaker, Lau, and Hernandez (1997) provided the industrial view that students should be provided with tools so they can develop in their mind a model of how a process should behave, both in the steady state sense and in the dynamic sense. The chemical engineering undergraduate curriculum emphasizes time domain ideas: flow rates, residence times, rate constants, etc. This is contrasted with electrical engineering where a frequency response of a circuit displayed on an oscilloscope is part of their bread and butter. Thus it would make sense that the electrical engineer be taught control concepts in the frequency domain, while chemical engineers be taught the same concepts in the time domain. Ramaker et al. suggested that frequency domain analysis and design should be taught at a graduate level, tieing the undergraduate curriculum closely to the time domain. A similar view was echoed by Eastman Chemical control engineers in their review of this paper.

Complex dynamic systems (such as bio) are most effectively addressed in the time domain. Nonlinear analysis techniques can be introduced explicitly in the time domain, thereby exposing students to theoretical concepts and analysis tools with wider applicability than Laplace domain methods. Moreover, the formulation of large-scale system models (in terms of state and/or input–output dimensions) is more readily performed in the time domain via conservation equations and state-space models (e.g., Henson, 2003; Sorensen, 1985). Connections with the corresponding Laplace domain concepts can be introduced as necessary (e.g., stability via eigenvalues versus poles in the s-domain).

On the other hand, state-space analysis of systems with time delays and/or zero dynamics in the time domain poses some challenges. Numerical simulation of these systems is straightforward, but analysis in the time domain is more cumbersome. Analytical treatment of zeros in the time domain is more involved than the corresponding Laplace domain methods for SISO linear systems. Linear state-space models treat delays in a discrete-time framework by performing state augmentation and using shift matrices, although this approach can lead to potentially large state dimensions. Multiple delays in a closed-loop block diagram produce more complicated state-space models that are problematic to develop and analyze. In these cases Simulink and transfer functions may provide an easier approach.

A related issue in the undergraduate course is the time spent on the design of PID controllers. It is clear from a review of current process control texts that there are many ways to tune a PID controller. Methods based on stability considerations alone are generally not satisfactory; available performance-based methods are both stable and predictable with respect to the design criteria. For simple systems, most tuning methods give approximately the same results. Therefore the instructor, rather than giving in to a veritable "fiddler's paradise," should be selective in the methods presented. The effect of model errors should also be addressed. While the tuning of a PID controller is straightforward for a nominal model, variations in model parameters should be taken into account because it is the normal situation. Trial and error tuning using software such as Simulink is one practical way to evaluate controller robustness. If biosystems inside the body are the main emphasis in a process control course, PID controllers should probably receive limited coverage, although many biomedical devices utilize PID controllers.

What about the model-based controller design approach that is presented in the leading control textbooks? Eastman Chemical control engineers report that they almost always receive requests to improve loop tuning on-line rather than using the step test method, because of time efficiency. Certainly for important loops the step test method can be applied and works fine.

However, when loops are performing poorly, being able to look at the trends, and current tuning, and say, "increase the gain", "stretch out the reset", or "this isn't a tuning problem, it's a valve problem," is very important. The industrial author of this paper states, "Recent graduates have zero ability to do such analysis. The most requested training from new employees is process control because they didn't learn any of this in school. Not to say that everyone should be a loop tuner upon graduation, but at least graduates should understand that processes need to be controlled and this skill might be important down the road. When introducing PID tuning, focus on the basic equation and the impact of what the gain and integral terms are doing. Sometimes there may be too much focus on the tuning rules and not enough on the perspective of what each part of the equation is doing".

With hundreds or thousands of loops, the principal goal is to have tuning and control that works reasonably well all the time, in contrast to controllers that work at optimum performance some of the time and need attention some of the time. Many times loops are tuned for peak performance at a given operating condition, only to be returned to more sluggish (but robust) settings at a later time when process conditions have changed.

4. Use of simulation and laboratory exercises to reinforce learning of process control concepts

4.1. The simulation experience

Practicing engineers in industry now find that the use of computer simulation tools is widespread. The engineer who knows how to effectively use modeling software has a significant advantage. The skills needed are not the details of syntax and software package familiarity and not even a particular adeptness in numerical methods. Instead, insight on how to use process design specifications, how to handle trace components that build up to significant amounts within a plant, dealing with captive components, and building models to match process operating data are all stumbling blocks that cause ineffective modeling in industry. In addition, dynamic modeling can be used very effectively in conjunction with steady state modeling, however, graduates have little experience writing unsteady state balances and understanding how such balances can be used.

Faculty from the systems area believe the entire chemical engineering curriculum can be revised to make it more model-based. Students should connect the basic idea of dynamic simulation to the solution of differential equations soon after obtaining the appropriate mathematics background instead of the 1 or 2 year hiatus that normally occurs. Beginning with the material and energy balance course, as students progress through various courses, the appropriate models would be developed as pedagogical tools, and state variable models should permeate the curriculum. For instance, in thermodynamics, instead of learning about flash calculations in the abstract, the students could develop a dynamic model of a flash drum. In unit operations, dynamic models of heat exchangers and distillation columns could be presented, although students should learn how models are developed, including the assumptions involved. Then, when

they get to the process control course, students would already have the basic background in process modeling. In teaching process control, the low level of modeling ability is a major limitation, so emphasizing it throughout the curriculum might help.

The design experience should focus more on operations than on design of equipment. Operations could cover topics such as simulation, operability, flexibility, and safety that may not be normally covered in the traditional design course. Industrial feedback to the authors of this paper stated that design of process equipment is not widespread in most operating companies. As fewer plants are being built and as design procedures are becoming more standardized, there is less design of heat exchangers, columns, etc. There is more attention paid to process design from a plantwide viewpoint and to debottleneck facilities and analyze each process from a plant perspective. Thus the design of the individual pieces of equipment is becoming more "cookbook", requiring expert advice on only a subset of designs. Basic exchanger design/sizing and basic column design in the mass transfer and stagewise classes provide good case studies to drive home the applicability of theory. However, as courses delve deeper into the special design cases, valuable time is lost.

If dynamic modeling is covered earlier in the chemical engineering curriculum, the control course could focus on the utilization of dynamic models for control purposes rather than setting them up from first principles, which can be best accomplished in other core chemical engineering courses. That allows the instructor to focus on relevant control issues like the extent of required modeling sophistication, e.g., nonlinear versus linear approximations, effects of parameter uncertainties, neglecting secondary physical phenomena, trade-offs between model accuracy and control performance and stability. Dynamic models can be used in the control course to improve understanding of a given process, give students experience in running complex units and dealing with emergency situations, and optimize process operating conditions. Dynamic models would be an integral part of case studies on process control (see Section 4.4).

4.2. Laboratory courses and process control

From the earliest days of engineering education, instructional laboratories have been an essential part of undergraduate programs. The specific goals of various laboratories in chemical engineering depend on the level (third or fourth year), the faculty teaching the laboratory, and the financial resources devoted to the laboratory facility. Sometimes laboratory experiments are focused on particular configurations that can illuminate the principles of fluid flow, heat transfer, or mass transfer, or to give students experience with a pilot-scale unit operation. In the area of process control, the laboratory can be used to illustrate dynamic responses, to deal with sensor dynamics, or to allow students to perform controller tuning with an actual control system connected to a process, thus reinforcing the lecture material on sensors, final control elements, signal transmission, and controllers. Most faculties come from experimental research backgrounds, so there is a clear identification with the importance of experimental experiences (although the unit operations

Table 4
Typical laboratory experiments in process control

Dynamic testing of various control components
Valve characteristics
Heat exchanger dynamics and control
Level control of tanks in series
Thermal response of fixed bed
Thermocouple calibration and dynamic response
Control of tank pressure
pH control
Cascade control of a heated bar
Distillation column control
Impulse testing of a mixing tank
Feedback controller modes and tuning
Four tank system (dynamics and control)

laboratory is usually not a preferred course for tenured and tenure-track faculty to teach).

Process control laboratory experiments demonstrate to students that processes will not behave as expected unless they are controlled. Being able to cause material to flow, heat up, react, cool, decant, etc. provides a strong sense of what it takes to actually make a process work. It also clearly points out the dimension of time, which is almost non-existent in other chemical engineering courses that assume steady state operation. We believe that understanding the non-steady state element is so important that a student should not obtain a degree without such exposure.

A number of universities have historically maintained a dedicated laboratory course as part of the process control sequence, but the number of independent lab courses is shrinking, due to the heavy resource requirements of lab courses and the pressure to reduce the number of hours in the chemical engineering curriculum. While some departments run both a junior measurements lab and a senior unit operations lab, many departments now operate only a single lab in the senior year, which may or may not incorporate control-related experiments. Table 4 shows a representative list of experiments where principles of process control have been demonstrated in various department labs over the years (e.g., Ang & Braatz, 2004; Skliar, Price, & Tyler, 1998).

Laboratory courses are evolving, and new directions are being examined at specific universities, combining elements of simulation and also distance learning. In the chemical process industries, the high cost of pilot-scale equipment and operating manpower has led to more reliance on computer-based simulations rather than traditional pilot-scale experiments. During a typical day, the plant engineer works from a control room, or at least behind a computer screen. An engineer rarely is in the field adjusting valve positions, flow rates, and temperatures, because that is normally done using the computer interfaces of distributed control systems.

The fourth-year unit operations laboratory at Texas Tech University is emulating industrial practice, by providing computer-generated simulations based upon mathematical models for laboratory equipment (Wiesner & Lan, 2004). The unit operations laboratory can familiarize students with safety concerns and operational issues regarding each piece of equipment. Major pieces of equipment include a double-pipe heat exchanger, an ammonia gas-absorber packed column, and a cooling tower. The

Virtual Unit Operations Laboratory (VUOL) complements the existing laboratory in order to give students a realistic experience with industrial operations. LabVIEW computer interfaces of the VUOL permit students to control the equipment in addition to physically turning valves and checking temperatures.

In the Texas Tech course each student operates two physical and two virtual experiments. Based on preliminary assessment data, students reported that this type of laboratory class contributed either a great deal or considerably in all areas of ABET criteria a–k. Virtual and physical experiments complement each other and enhance student learning. In addition, there appears to be no significant difference in the student perception to their learning in using virtual versus actual unit operations experiments, in 18 out of 20 ABET-related skill areas. While students believe both types of experiments are valuable, a total virtual unit operations laboratory would apparently not be well-received by the students. With the physical portion of the lab, students get a feel for the equipment and how it operates. With the virtual portion, the students become familiar with the computer interfaces that are similar to industrial control rooms, and learn to manipulate the equipment via those controls instead of manually turning valves and knobs. They can also explore operating scenarios which are not easily or economically investigated with physical equipment.

4.3. Remote laboratory experiments

Another approach for laboratory experiments is to use a computer connected to the Internet to allow students to operate equipment in a remotely located physical laboratory. This permits students to operate real laboratories at any time, from anywhere, using standard digital communication software such as web browsers. One advantage of such remotely accessible laboratories is that a teacher and students at another institution can have access to laboratory facilities without incurring the full cost of developing such resources. This advantage is significant when one recognizes that building a chemical engineering laboratory costs approximately $1000 per square foot, in addition to costs for maintaining and replacing equipment and hiring technician support. With highly automated experiments, a significant reduction in teaching assistant time requirements is possible.

Web-accessible laboratory experiments, controlled and monitored interactively by computers that are connected to the Internet, have been available for more than 5 years. This capability is available in chemical engineering laboratories at University of Tennessee-Chattanooga (Henry, 2001) as well as other schools, such as University of Texas (Rueda & Edgar, 2003), MIT (Selman et al., 2005), and EPFL (Gillet, 2006). With appropriate planning, faculty and students from another university can run some of the web-connected experiments at any time of the day or night, any day of the week. The laboratory station's computer operates the equipment (pumps, valves, heaters, relays, etc.), collects the data (pressure, temperature, concentration, etc.) and sends it to the web user. The UT-Chattanooga site is very extensive; see http://www.chem.engr.utc.edu/. From the web page students can link to tutorials, pictures, live video and past data files. Graphs tracking the dynamic process vari-

ables are separately available on the Web. These web pages can be viewed simultaneously by other students or instructors in real-time. The web page and all the raw data are archived for subsequent viewing and analysis.

Using such highly automated experiments for remote operations can allow a drastic reduction in the amount of personnel time required for those particular experiments. In addition, by sharing the operation of the experiments among several universities, there can be a pro rata reduction in maintenance costs. There is also the opportunity to use this technology to add experimental demonstrations or assignments to a lecture. Furthermore, during a lecture it may be desirable to have students individually or in small groups carry out an experiment in class, much like a traditional paper-and-pencil in-class assignment; in contrast, a traditional experiment would require continuous supervision by teaching assistants.

4.4. Problem-based learning and the case study approach

Problem-based learning (PBL) is an approach that is not typically used in chemical engineering departments but one that becomes more important in an integrated curriculum (Boud, 1997; Woods, 1994), such as envisioned in the Frontiers effort discussed in Section 1.2. As the students in a PBL curriculum work with a problem, they should be able to identify what they need to learn and what resources they are going to use to accomplish that learning. In this way students can customize their learning (as they all have differing levels of knowledge and experience). Allowing students to have the opportunity to assume this responsibility, under faculty guidance, prepares them to become effective and efficient lifelong learners. This means that the teachers working with the students should not provide the students explicit information needed nor give them reading or study assignments. The students must decide what they need to learn and to seek out appropriate learning resources, using the faculty as consultants as well as books, journals, online resources and other experts. Hence PBL is not teacher-centered, and the teacher does not direct how the students attack the problem or what resources they should use. Instead the teacher designs and provides the problem simulations and other experiences that challenge the students to learn what is expected in the course. The teacher acts as a facilitator, giving students assistance in their work with the problem as they develop problem-solving skills, identify what they need to learn, and develop self-directed learning skills. Topics included in a traditional course still are intended to be covered in a problem-based learning environ-

ment, but probably in a different order and in a "just-in-time" fashion. While PBL is not teacher-centered, it is very intensive for the instructor who teaches this way, compared to the traditional approach.

As in the real world, PBL deals with ill-structured problems, stimulating learners to generate multiple hypotheses about their cause and possible solution. These ill-structured problems must be selected and designed to allow students to freely inquire through observation, interview, review of records or performing simulations in order to obtain information needed to support or verify their hypotheses. Student collaboration occurs naturally during the group's discussions with the professor. However, the students must be encouraged to collaborate by forming teams during their self-directed study, which can be the most rewarding and productive part of their learning.

Problem-based learning should not be confined narrowly to a single discipline or subject. Information should be integrated from all the disciplines that are core to the degree program and relevant to the problems presented. Process control is one of the few courses in the chemical engineering curriculum which readily permits such integration of multiple subjects. Control could also be taught with part of the course devoted to PBL, and it is believed that many control faculty employ some elements of PBL when they teach the class. The justification of such a pedagogical approach is that students need to see the thought process used in formulating and solving a problem, which does not happen with a "canned" presentation.

Marlin and Woods (2002) give an example of a troubleshooting exercise that is utilized in the PBL approach. A fired heater has been functioning under control for many weeks, but recently the feed rate has been increased. Suddenly the exit temperature begins to decrease and the fuel to the heater also increases, both rates accelerating rapidly. The student is expected to use process fundamentals and qualitative analysis to diagnose the problem and propose corrective action, both from an operations point of view but also by considering a design change. For other process examples, see http://www.pc-education.mcmaster.ca/operability/operability-home.htm.

Another approach to address the challenge of depth of treatment versus limited classroom time is the case study method (Bequette, Schott, Prasad, Natarajan, & Rao, 1998; Mustoe & Croft, 1999). The process control modules by Doyle et al. (2000) and Bequette (2003) are two resources for simulation-based case studies in process control. The Frontiers effort has identified a number of potential case studies relevant to emerging technologies that could be a course-long emphasis; see

Table 5
Possible case studies for the process dynamics and control course (MIT, 2006; Parker et al., 2004)

Chemical processes and materials processing
Fed-batch polymerization reactors; desalination of seawater; crystallization in drug manufacture; continuous pulp digester; paper machine; hydrogen from biomass or coal; batch processing in a semiconductor process (e.g., lithography); photovoltaic film processing; fuel cell
Biotechnological systems
Continuous and/or fed-batch fermentors; yeast energy metabolism; cell stress response (e.g., heat shock); eukaryotic cell cycle; bacterial chemotaxis
Biomedical systems
Baroreceptor vagal reflex (blood pressure control system); insulin-dependent diabetic patient (glucose–insulin metabolism/control); circadian rhythm gene regulatory network; anesthesia control; drug delivery for HIV treatment; drug-delivery for cancer treatment

Table 5. For a biosystems analysis, a case study framework for an insulin-dependent diabetic patient with appropriate references has been mapped onto the course outline (Parker et al., 2004). To aid in teaching the course, a well-documented case study could be useful for faculty who are not dynamics and control experts.

4.5. Innovative lecture-based approaches for teaching process control

Experienced engineering faculty recognize that 21st century university students are different from the graduates prior to 1990. The new digital generation is not intimidated by computers, demands interaction, views learning as a plug and play experience, would not read a manual but learns through experimentation, and may not learn best through the linear seriatim process. In fact, their brains may be wired differently, at least in a neural sense. As personal computers, fiber optics, and digital networks have expanded into homes and businesses, these students expect the ubiquitous availability of information technology in their classes (but their choice of devices may differ from those of the faculty).

Technology-enhanced learning environments in a course like process control can interact effectively with students across both time and distance, and expand the information horizons of students. Technology can facilitate interaction with students through simulations of logical and physical systems as well as in the observations of actual data, which can be generated in real-time. Use of technology in teaching is classified as an active learning approach (Prince, 2004).

Information technology enables a new form of teaching and learning in which pure lecturing to passive students can be replaced by an integrated lecture/laboratory situation. In this mode the instructional material is presented on the computer with the conceptual elements explained and supplemented by the instructor's lecture. At the end of the presentation, a simulated laboratory exercise is executed on computers under the supervision of the instructor to give experience in application of the concepts or processes. This approach using computer simulations is embodied in the studio teaching method developed at Rensselaer Polytechnic Institute, which has been used by one of the authors to teach the process control course (Bequette, 2005).

If the classroom has individual computers (typically in a wireless environment), students can access data and can perform their own calculations (or in small groups). During this time, the lecturer can move among the students, looking over their shoulders and serving as an advisor and facilitator. Teaching and learning in this case can become more of a one-on-one or small group exercise and less of a standard lecture exercise. This integrated lecture/laboratory mode of instruction has been used successfully in industrial training, particularly in the software industry. Learning and cognitive studies have shown definitively that technology used to personalize learning via immediate feedback and visual content has significant impact on the retention of knowledge by the students compared to the traditional lecture format.

In the studio approach, mini-lectures can be presented when it is clear that there are common problems and misunderstandings.

Also, immediate "corrective feedback" to minimize the frustration with learning new software (and differentiating between incorrect use of the software versus an incorrect problem solution formulation) is absolutely critical. It should be recognized that a studio-based course takes more contact hours than a standard lecture course. For example, at RPI control is a four-credit course taught 3 days/week, 2 h/day for the spring semester of the junior year. Before using a studio classroom, the RPI course had a traditional 3 h/week lecture, with a computer lab session one night/week. It was absolutely critical to have the instructor, or a good TA, at the computer lab sessions to minimize frustration with the software. Also, the separate lab approach resulted in some decoupling of material, while the studio allowed simulation studies to immediately follow the lecture material. The goals of the studio exercise should be clearly laid out to the students. It is important to have capable TAs who can move around the room and assist students. TAs who provide inconsistent or wrong advice to the students are a major problem in this course.

5. Conclusions and recommendations

5.1. "Predictions are often difficult, especially about the future"

This quote has been attributed to both Niels Bohr and Yogi Berra. Edgar (1990) forecasted the process control industrial environment and appropriate course content for the year 2000: "The industrial environment where process control is carried out will probably be quite different from what it is today. In fact, some forward-thinking companies believe that the operator in the factory of the future will be a B.S. engineer. Because of greater integration of the plant equipment, tighter quality specification, and more emphasis on maximum profitability while maintaining safe operating conditions, the importance of process control will be increased. Very sophisticated computer-based tools will be at the disposal of plant personnel, who will at least need to understand the functional logic of such devices. Controllers will be self-tuning, operating conditions will be optimized frequently, total plant control will be implemented using a hierarchical (distributed) multivariable strategy, and expert systems will help the plant engineer make intelligent decisions (those he or she can be trusted to make). Plant data will be analyzed continuously, reconciled using material and energy balances with optimization, and unmeasured variables will be reconstructed using parameter estimation techniques. Digital instrumentation will be more reliable and composition measurements which were heretofore not available will be measured on-line. There are many industrial plants that have already incorporated several of these ideas, but no plant has reached the highest level of sophistication over the total spectrum of control activities". It is fair to say that this description is a reasonably accurate assessment for many operating plants in 2006.

Edgar (1990) also proposed a 15-week "leading edge" lecture course forecasted for the year 2000, which included the following topics: (1) dynamic simulation, (2) response characteristics, (3) development of discrete-time models, (4) analysis of discrete-time systems, (5) conventional and predictive con-

Table 6
Advanced topics for undergraduate process control

Alarms and safety
Model predictive control
Simulation
Distributed control software and hardware
Unit operations control applications
Batch sequence control, PLCs
Process control languages
Statistical process control and monitoring
Process control data base management
Real-time computing
Expert systems, artificial intelligence
Digital control algorithms
State-space analysis
Real-time optimization
Model identification

troller structures, (6) optimization methods for controller design, (7) tuning of controllers/robustness, (8) feedforward, adaptive, and multivariable control, (9) digital hardware implementation, and (10) expert systems. The selection of topics can be justifiably criticized because it presupposes a reasonable level of training in a field such as optimization. However, the student does not need a deep understanding of the numerical details involved in order to have confidence in the answers. Even today linear and nonlinear programming tools have matured to the point that they are used routinely by students (e.g., Excel Solver).

During the next 10 years will the PID controller be replaced by a more general approach based on nonlinear programming? The PID controller provides reasonably good control with a minimum of modeling effort. Industrial practitioners believe the effort required to set up a nonlinear program for single-loop control is large and in most cases not justifiable. This is why a small percentage of single-loop model predictive control schemes have been implemented. An alternative viewpoint has been asserted by Pannochio, Laachi, and Rawlings (2005), which presents a computationally fast solution to implement single-loop MPC controllers.

For the vast majority of control loops today there appears to be no issue of digital versus analog control, so covering discrete-time models and controllers is probably not necessary. The lowest level of control (constituting >80% of the loops) will continue to be a simple PI flow controller. The sampling rate is high at this level, so there is not a vast difference between digital and analog control. The main advantage of digital implementation at this level is the ease of maintenance. If a particular control strategy is ineffective, digital technology allows a quick retrofit. Therefore coverage of discrete-time control mathematics is probably not necessary for undergraduates.

The dilemma process control educators face is the breadth of material that could be covered in a 12–15 weeks course. Table 6 illustrates the variety of advanced topics, several of which could be justifiably covered in an undergraduate course. So the process control instructor must perform a balancing act to cover the key ideas as well as optional topics in a single course.

In order to make room for new material in the undergraduate process control course, including biosystems, the following

steps can be taken:

(1) de-emphasize frequency response but keep Laplace transforms;
(2) reduce coverage of multiple approaches for PID controller tuning;
(3) increase use of simulation in sophomore and junior chemical engineering courses, so students are well-prepared for dynamic simulation when they take the control course. Use more dynamic simulation in the capstone design and operations course;
(4) introduce a number of short laboratory experiences that allow students to collect actual dynamic data, analyze the data, and use a controller to influence the behavior (as part of the process control course);
(5) use case studies to show how process control can be employed to solve real engineering problems. This will help in introducing non-traditional areas such as biotechnology and nanotechnology into the control course;
(6) teach process control in the senior year, given that it is valuable integration course with many connections to other chemical engineering courses.

Separate process control courses are beginning to disappear in some departments, and this trend will increase in the future. The academic process control and industrial communities need to promote the viability and visibility of process control as an important course for chemical engineers. Without a solid understanding of the concepts of dynamic systems and feedback control, chemical engineers cannot make a unique contribution to emerging as well as traditional technologies. One can argue that it is a systems approach that truly separates engineers from chemists and biologists. If we remove or dilute this perspective in the education of chemical engineering undergraduates, then they will not have this unique perspective to offer and will not be valued as highly.

Most educators and industry practitioners agree that a systems viewpoint is valuable for chemical engineering graduates. However, as more chemical engineering research moves toward science and away from engineering, there is an important component that is lost. The strength of engineering is that ideas are brought to industrial reality—products are made for society on a large scale in an economic way. This involves not only creativity and innovation on the front end, but also includes the day-to-day operation, control, and management of facilities for years to come. If chemical engineering graduates are not trained to function in either environment, then we have missed the mark. A chemical engineering graduate has traditionally been a valuable employee in a wide variety of roles not only because of their ability to understand mass transfer on a molecular level, but also because of their ability to understand and make sense of complex mechanisms that manipulate chemical processes.

Dynamics, feedback, and stability are intellectual underpinnings arising out of the current control course required for understanding many new and complex systems of interest to chemical engineers. Control, like design, can be taught in a way so that students must integrate knowledge from other core chem-

ical engineering courses in process modeling and analysis of process behavior. There are not many courses in the curriculum that fulfill these needs. Constructive change is critical to the health of our profession, so it is vital that faculty from the computing and systems community join this discussion to renovate the curriculum and specifically the process control and related courses.

References

AIChE, 2002–2003. *Initial placement of chemical engineering graduates*. http://www.aiche.org/careerservices/trends/placement.htm.

Ang, S., & Braatz, R. D. (2004). Experimental projects for the process control laboratory. *Chemical Engineering Education*, *36*(3), 182–185.

Bequette, B. W. (2003). *Process control: Modeling, design and simulation*. Upper Saddle River, NJ: Prentice-Hall.

Bequette, B. W. (2005). A laptop-based studio course for process control. *IEEE Control Systems Magazine*, *25*, 45–49.

Bequette, B. W., Schott, K. D., Prasad, V., Natarajan, V., & Rao, R. R. (1998). Case study projects in an undergraduate process control course. *Chemical Engineering Education*, *32*(3), 214–218.

Boud, D. (1997). *The challenge of problem-based learning* (2nd ed.). Kogan Page.

Cussler, E. L., Savage, D. W., Middleburg, A. P. J., & Kind, M. (2002). Refocusing chemical engineering. *Chemical Engineering Progress*, 265.

Doyle, F. J., Parker, R. S., & Gatzke, E. P. (2000). *Process control modules: A software laboratory for control design*. Upper Saddle River, NJ: Prentice Hall.

Edgar, T. F. (2000). Process control education in the year. *Chemical Engineering Education*, *24*, 72–77.

Edgar, T. F., & Rawlings, J. B. (2004). Frontiers of chemical engineering: The systems approach. In *DYCOPS proceedings, paper 206*.

Gillet, D. (2006). *Ecole Polytechnique Federale de Lausanne*. http://www.lawww.epfl.ch/page4227.html.

Henry, J. (2001). Web-based laboratories: Technical and pedagogical considerations. In *Proceedings of the AIChE annual meeting*, available at http://www.chem.engr.utc.edu/Henry-Pub.

Henson, M. A. (2003). Dynamic modeling of microbial cell populations. *Current Opinion in Biotechnology*, *14*, 460–467.

Kitano, H. (2002). Systems biology: A brief overview. *Science*, *295*, 1662–1664.

Marlin, T., & Woods, D. R. (2002). Troubleshooting for CAPE undergraduate education. In *Proceedings of the ESCAPE 12*.

Massachusetts Institute of Technology (MIT) (2006). *Frontiers in chemical engineering education initiative*. http://www.web.mit.edu/che-curriculum/.

McCarthy, J. J., & Parker, R. S. (2004). The pillars of chemical engineering: A block-scheduled curriculum. *Chemical Engineering Education*, *38*(4), 293–301.

Mustoe, L. R., & Croft, A. C. (1999). Motivating engineering students by using modern case studies. *International Journal of Engineering Education*, *15*, 469–476.

National Academy of Engineering (NAE). (2004). *The engineer of 2020: Visions of engineering in the new century*. Washington, DC: National Academies Press.

National Research Council (NRC). (2003). *Board on Chemical Sciences and Technology, beyond the molecular frontier, challenges for chemistry and chemical engineering*. Washington, DC: National Academies Press.

Ogunnaike, B. A., & Ray, W. H. (1994). *Process dynamics, modeling, and control*. New York: Oxford University Press.

Pannochio, G., Laachi, N., & Rawlings, J. B. (2005). A candidate to replace PID control: SISO constrained LQ control. *AIChE Journal*, *51*, 1171–1189.

Parker, R. S., Doyle, F. J., & Henson, M. A. (2004). Integration of biological systems content into the process dynamics and control curriculum. In *DYCOPS proceedings, paper 212*.

Parker, R. S., Doyle, F. J., Henson, M. A. (2006). Integration of biological systems content into the process dynamics and control curriculum. *Chemical Engineering Education*, *40*(3).

Parker, R. S., Ward, J. H., Peppas, N. A., & Doyle, F. J. (2000). Robust H_∞ glucose control in diabetes using a physiological model. *AIChE Journal*, *46*, 2537–2549.

Prince, M. (2004). Does active learning work? A review of the research. *Journal of Engineering Education*, *93*(3), 223–231.

Ramaker, B. L., Lau, H. K., & Hernandez, E. (1997). Control technology challenges for the future. CPC-V conference. *AIChE Symposium Series*, *93*(316), 1–7.

Rueda, L., & Edgar, T. F. (2003). Process dynamics and control experiments carried out over the Internet. In *Proceedings of the AIChE annual meeting*.

Seborg, D. E., Edgar, T. F., & Mellichamp, D. A. (2004). *Process dynamics and control* (2nd ed.). New York: Wiley.

Selman, A., Goodson, M., Kraft, M., Sen, S., McNeill, V. F., Johnston, B. S., & Colton, C. K. (2005). Performing process control experiments across the Atlantic. *Chemical Engineering Education*, *39*(3), 232–237.

Shinskey, F. G. (2002). Process control: As taught vs. as practiced. *IEC Research*, *41*(16), 3745–3750.

Skliar, M., Price, J. W., & Tyler, C. A. (1998). Experimental projects in teaching process control. *Chemical Engineering Education*, *32*(4), 254–257.

Sorensen, J. T. (1985). *A physiologic model of glucose metabolism in man and its use to design and assess improved insulin therapies for diabetes*. PhD thesis, Department of Chemical Engineering, MIT, Boston, MA.

Stephanopoulos, N., Solis, E. O. P., & Stephanopoulos, G. (2005). Nanoscale process systems engineering: Towards molecular factories, synthetic cells and adaptive devices. *AIChE Journal*, *51*, 1852–1869.

Wiesner, T. F. & Lan, W. (2004). Comparison of student learning in physical and simulated unit operations/experiments. *J. Engr. Educ.*, *93*, 195–204. See also http://www.che.ttu.edu/vuol.

Woods, D. R. (1994). *Problem-based learning: How to gain the most from PBL*. Waterdown, Ontario (available from the author).

Yang, D. R., & Lee, J. H. (2002). Process control education software using Java applets. In *Proceedings of the AIChE annual meeting*, http://www.chbe.gatech.edu/faculty/lee/che4400/javamodule.html.