IDEAS TO CONSIDER FOR NEW CHEMICAL ENGINEERING EDUCATORS: PART 2

(Courses Offered Later in the Curriculum)

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Although teaching is a critical mission of any college or university, the heightened research aspirations of many institutions necessitate that faculty members spend less time on instructional activities, at least if that new professor wants to exceed the research standards set for tenure and promotion. Thus, when a faculty member is tasked with teaching a new course, developing a good set of instructional materials can be a challenging, time-consuming task. In this paper we review some of what we consider the best practices in engineering education applied to the following courses: solution thermodynamics; heat and mass transfer; kinetics and reactor design; process control; and senior design.

We note that this work was first presented at the 2007 ASEE Summer School[1] and published in the 2009 ASEE conference proceedings as paper #AC 2009-29,[2] although updated here to reflect more recent works. Also, note that a companion paper that covers those chemical engineering classes that normally occur earlier in the curriculum (freshmen chemical engineering; material and energy balances; fluid mechanics; introductory thermodynamics; and separations) was presented at the 2007 ASEE Summer School[3] and is published in the 2008 ASEE Annual Meeting as paper #AC 2008-1147,[4] the 2008 AIChE conference proceedings,[5] and within the Summer 2009 issue of *Chemical Engineering Education*.[6] Furthermore, the reader may be interested in viewing recorded oral presentations from the 2008 AIChE Centennial Topical Conference on Education for these and other core chemical engineering subjects at the AIChE Education Division website.[7]

The format used for each course is:

- *Brief description of typical course scope*
- *Discussion about novel and successful methods used, including best practices and new ideas*
- *Listing of "toughest concepts" for the students (and suggestions on how to address them)*
- *Authors' experiences with methods used in teaching the course*

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SOLUTION THERMODYNAMICS

This course, also commonly called Thermodynamics 2, focuses on mixtures and mixture phase equilibrium as well as reaction equilibrium. Unlike the first thermodynamics course, this course normally consists of exclusively chemical engineering students. Note that since this is typically the second part of a two-part Thermodynamics sequence, some of the advice/ideas/information given for the first Thermodynamics course in our previous work[3-6] are applicable to the Solution Thermodynamics course.

Best Practices / New Ideas

There are certain phenomena within this course that, although working against intuition, can be visualized through experimentation (both desktop and simulation). For example, consider the following straightforward demonstrations that can be performed to show mixture effects:

- *Heat of solution – Mix salt into water and, using a thermocouple placed in the solution, have the students attempt to estimate the heat of solution.*
- *Excess volume – Take a long, thin container and mix 500 ml of ethanol with 500 ml of water. The resulting solution is ~970 ml, which demonstrates that liquid volumes are not additive.*
- *Miscibility – One can show how the ethanol + water and the ethanol + toluene mixtures are miscible, yet the toluene + water mixture forms a miscibility gap.*[8]

Additionally, since changes in molecular-level interactions can manifest themselves in complicated phase behavior, simulation can be utilized to demonstrate these effects in a powerful way. One source for this information is the website for the Etomica environment created by Kofke, which houses many applets, some of which focus on fundamental behavior germane to an undergraduate solution thermodynamics course.[9]

Other recent ideas used to best teach the concepts of this course include:

- *Show students exceptions to the well-known Le Chatelier's Principle.*[10]
- *Promote a graphical view of thermodynamics that emphasizes uncommon intuition*[11] *and focuses on the benefits of visualization using modern software, such as Mathcad.*[12]
- *Falconer emphasizes the use of concept tests that use classroom response systems to allow immediate feedback from students for formal or informal assessment.*[13]
- *Initiate a discussion on the complications of calculating liquid-liquid phase equilibrium and the potential for false solutions; for example, when the initial guess for the iterative method is too far from the actual solution, it is possible to converge to a local and not a global minimum.*[14]
- *An MS Excel add-in (XSEOS) calculates a variety of thermodynamic properties using both equations of state and Gibbs excess energy models.*[15]
- *There are various applications of a cubic equation of state in calculating mixture phase diagrams and chemical equilibrium using MATLAB (with programs provided).*[16]
- *A recent work describes a combination of experimental and modeling approaches to introduce gas-liquid solubility.*[17]
- *Elliott provides an interesting discussion relating solution non-ideality, including hydrogen bonding, to solubility and volatility in both a qualitative and quantitative manner.*[18]

It is also noted that thermodynamics is a subject area not just encountered in chemical engineering, but in mechanical engineering, chemistry, physics, and other disciplines. Accordingly, educational ideas from those disciplines exist related to thermodynamics, and the interested reader might well want to consider insights and ideas from faculty outside of chemical engineering. For example, the *Journal of Chemical Education* (published by the American Chemical Society) contains many educational articles related to thermodynamics, such as recent contributions on an experimental technique for obtaining Henry's Law coefficients[19] and a laboratory procedure for gas clathrate hydrates.[20] *The Physics Teacher* discusses various fundamental thermodynamics concepts as well as some interesting analyses, such as the thermodynamics of a thermos.[21] Articles on the design of a bench-top, portable refrigeration apparatus for use in a classroom setting can be found in the *International Journal of Mechanical Engineering Education*.[22] Also, *Computer Applications in Engineering Education* publishes articles related to thermodynamics education, such as a recent contribution on the creation of residue curve maps for multi-component mixtures using MATLAB and Mathematica.[23]

Finally, one can utilize this class (or the previous Thermodynamics class) to provide an opportunity for students to design, estimate costs, build, and implement a project related to course concepts. In such an exercise, students are expected to keep track of their budget, set milestones, take notes to record their successes and failures, and prepare a detailed report. Industrial visitors may be interested in attending and reviewing the presentations. To promote efficiency and reuse, projects in the following year can be used to improve upon the existing design. Some example projects have demonstrated ethanol distillation through building a still and the appearance of miscibility gaps at different temperatures for the water + propylene glycol n-propyl ether system.[24]

Trouble Spots

Trouble spots for this course include:

- *Often students become bogged down in the calculations and lose the big picture. Phase equilibrium calculations for mixtures (especially with equations of state) are complicated, and there is a tendency to work towards arriving at an answer with little appreciation or interpretation of the result. Depending on the situation, the use of an Excel add-in such as XSEOS*[15] *or a web applet to determine phase equilibrium from an equation of state may be more appropriate.*[25, 26]
- *Reading mixture phase diagrams can be confusing to*

students. By utilizing the Journal of Chemical and Engineering Data*, students can find a wide variety of phase diagrams that can be used to spark discussions on the Gibbs Phase Rule, Raoult's Law, miscibility gaps, etc.*

- *Nomenclature and symbols can be problematic, especially if there are discrepancies between the Thermodynamics course and the students' previous chemistry or physics course. In this course (and between different books), symbols have subscripts, hats, carats, superscripts, overbars, etc. A poster or handout that describes each modification to a symbol, posted in the classroom (or prepared for the student), could be of great benefit.*

Author Experiences

At Tennessee Technological University, the Solution Thermodynamics course and the Separations course have been merged into a single course with an integrated laboratory experience. This approach has the benefit of using the theories and models prevalent in solution thermodynamics more transparently applied in a separations process, be it binary distillation, crystallization, or liquid-liquid extraction. Additionally, the author readily incorporates the following in the Solution Thermodynamics course:

- *Open-ended, relevant design problems such as making ethanol starting from a bio-mass source (such as switchgrass)*
- *Incorporation of a critical-thinking framework*[27] *to examine claims related to course concepts/materials*
- *Homework problems tagged with Bloom's Taxonomy levels so that the instructor is reminded to strive towards problems and solutions that focus on analysis/synthesis/evaluation skills*
- *A square-well mixture Java applet*[9] *that allows the user to change the cross-interaction parameter and cause a very visual phase splitting; used in conjunction with a desktop demonstration of liquid-liquid phase splitting, provides a powerful micro- and macro-level examination of this phenomenon*
- *Generating Pxy or Txy diagrams using Raoult's Law for systems that need non-ideal approaches to motivate the use of such techniques; revisiting those same systems and incorporating both activity and fugacity coefficients, plotted with the experimental data, serves as a good reminder and contrast for the need for non-ideal approaches*

HEAT AND MASS TRANSFER

The field of heat and mass transfer was revitalized as a fundamental field of study in 1960 through the publication of the text *Transport Phenomena*.[28] Currently, heat and mass transfer remains a popular subject in the research literature.

Best Practices / New Ideas

Recent advances in simulation and modeling allow for a marked change in how heat and mass transfer can be taught in the classroom. There are several examples published in the literature using computational fluid dynamics,[29-31] numerical solutions,[32, 33] similarity solutions,[34] molecular simulations,[9,35, 36] and desktop modules.[37]

- *Sinclair*[29] *describes the use of Fluent software in the undergraduate curriculum. Although focused on fluid dynamics, the teaching principles illustrated in this paper can be extrapolated to heat and mass transfer courses.*
- *Thompson*[30] *utilizes the PDE toolbox feature in Matlab to solve a variety of problems in fluid mechanics, heat transfer, and solid mechanics.*
- *Keith, et al.,*[31] *employ COMSOL Multiphysics to illustrate how a variety of problems in fluid mechanics, heat and mass transfer, and reaction kinetics can be extended to fuel cell applications.*
- *Goldstein*[32] *solves free convection problems using similarity variables and a numerical simulation of an initial value problem.*
- *Binous*[33] *uses Mathematica to solve membrane permeation problems using the complete mixing model (algebraic solution) and the cross-flow, counter-current, and co-current systems (numerical solution).*
- *Subramanian*[34] *applies similarity methods to three classical problems: diffusion in a semi-infinite domain, flow past a flat plate, and the Graetz problem for flow into a rectangular channel with isothermal walls.*
- *Keffer, et al.,*[35] *illustrate the use of molecular-level simulations to predict gas diffusivities.*
- *Minerick*[37] *demonstrates ways to use desktop-sized modules to reinforce fundamental heat transfer concepts, including 1-dimensional heat conduction, the effect of contact resistance, steady-state and transient heat generation, and convection.*

There are many good websites with simulations appropriate for undergraduate students in heat and mass transfer courses. The following is a partial listing of those highlighted recently in the literature or at conferences:

- *As mentioned previously, the Etomica environment*[9, 36] *provides relevant Java-based molecular simulations on its website.*
- *Coker, et al.,*[38, 39] *describe simulation of gas separation using polymer membranes.*
- *Zheng and Keith*[40-42] *describe the use of Java applets to help students visualize heat and mass transfer.*

Two papers by Flynn, et al.,[43, 44] focus on integrating green engineering principles into a heat transfer course. The first paper[43] describes several traditional heat transfer problems that are uniquely coupled with green engineering principles.[45, 46] Example problems include: conduction shape factors and rainforest conservation, natural convection and energy-efficient lighting, natural convection through windows, life-cycle studies, and radiation heat transfer for comfort and energy efficiency. The second paper[44] describes assessment of the teaching tools.

Some novel experiments in heat and mass transfer include:

- *Investigation of transport of environmental pollutants in groundwater using dissolved pollutants and colloids*[47]
- *Experiments and modeling of lozenge dissolution to simulate drug delivery processes in the human body*[48]

- *Rate of drying curves and unsteady-state heat transfer in cooking of French fries*[49]
- *Designing, building, and testing of small compact heat exchangers*[50]
- *Carbon dioxide loss from a carbonated beverage container*[51]
- *Experiments and modeling of the hemodialysis of creatinine to enhance bioengineering experiences in the chemical engineering curriculum*[52]

Trouble Spots

Trouble spots for this course include:

- *Students may possess weak math skills. Instructors can develop handouts to step students through difficult solution processes (such as solving differential equations). Reference 53 contains an example. Instructors could also have students practice using in-class problems and homework assignments before testing them.*
- *Students may have difficulty in connecting highly theoretical content to real industrial applications—if there is an internet-connected computer and projector in the classroom, instructors can use online and/or laboratory demonstrations to make a strong connection. This connection can also help students with their follow-on classes.*
- *Students often do not know order-of-magnitude values for heat exchanger area, mass transfer coefficients, dimensionless groups, etc. The instructor can provide them with general values on a handout they can paste in the front of their textbook. For an example, see Reference 54 or the books by Woods*[55] *or Fogler.*[56]
- *Students struggle with knowing when to eliminate terms in the governing equations. If they are provided with the aforementioned handouts, they will be prepared for more advanced homework and exam questions.*

Author Experiences

At Michigan Technological University, efforts have been made to bring computer technology and hands-on problems into the Transport / Unit Operations 2 course. As such, the students have been introduced to simulations and modeling in various forms.

- *A homework problem has students design an oven for cooking turkeys following the Java applet of Zheng and Keith.*[40-42, 57]
- *Via homework assignments and a project, students are asked to create their own steady-state and unsteady-state finite difference models for mass diffusion in MATLAB.*
- *Students have a homework problem comparing the exact solution for a steady- or unsteady-state diffusion problem with that from COMSOL Multiphysics.*[31] *The students then have to solve a harder problem with the software (for which no analytical solution is available).*
- *Students are introduced to molecular modeling and how it is used to calculate transport properties.*[9, 35, 36]
- *Students are given experimental data from a laboratory course and are asked to use it to predict transport properties.*
- *Students are given daily handouts—the handouts are either meant to aid them in solving problems in transport phenomena (for example see Reference 53) or a daily in-class problem (following the principles of problem-based learning) where the students apply the lecture material they just learned.*

KINETICS AND REACTOR DESIGN

Kinetics, catalysis, and reactor design distinguish chemical engineers from other engineers and remain active research fields.

Best Practices / New Ideas

Like other subject areas, simulation and modeling are used in kinetics and reactor design. There are several examples published in the recent educational literature[58-64] that will now be summarized.

- *Stochastic simulations of chemical reactions*[58, 59]*: Martinez-Urreaga, et al.,*[58] *use MATLAB to simulate the reversible reaction A $\leftrightarrow$ B, while Fan, et al.,*[59] *simulate the thermal death kinetics of a cell population.*
- *Computational fluid dynamics*[60-62]*: Lawrence, et al.,*[60] *use CFX commercial software to incorporate non-ideal reactors into the curriculum. They develop residence time distributions in tubular reactors and use them to determine conversion for a reaction using Langmuir-Hinshelwood kinetics. Madiera, et al.,*[61] *simulate a complex two-dimensional reservoir, determine the residence time distribution and predict the conversion during steady-state operation. Bakker, et al.,*[62] *illustrate non-ideal effects in various reactor types with color images of CFD simulations.*
- *Parulekar*[63] *uses Mathcad to perform numerical simulations of several fundamental kinetics and reactor design problems, including estimation of kinetic parameters, autocatalytic reaction and space times for operation of continuous and plug-flow reactors, gas phase sulfur dioxide reaction to sulfur trioxide, predicting equilibrium composition of a reaction mixture, steady-state multiplicity in continuous reactors, membrane reactors, series-parallel reactions, and consecutive reactions.*
- *It is noted that reactions can also be simulated in process modeling software such as ChemCAD, Aspen, Hysis, and UniSim for various reactor types.*
- *Wilcox*[64] *describes the utility of computational quantum chemistry for solving advanced problems such as the development of rate expressions from transition state theory.*

A paper by Muske and Myers[65] integrates principles of statistics and experimental design into a project to determine the forward and reverse reaction kinetic rate constants for ethylene hydrolysis into ethanol. Complicating the problem is that students need to determine the Arrhenius parameters for these reactions. Students are given a budget and request "experimental" runs from which they are supplied data by e-mail one day after their request. A process simulation with statistical fluctuations is used to generate results and mimic a real experimental study. They must decide when they have enough data (or when they run out of money), and possibly adjust their experimental plan in order to perform the analysis.

The Safety and Chemical Engineering Education (SACHE) program is a joint effort between the American Institute of Chemical Engineers Center for Chemical Process Safety and academic institutions. Founded in 1992, the committee typically organizes a yearly workshop to educate chemical engineering faculty on the importance of safety education. Their website[66] features problem sets and web modules that can be used in the classroom. It is noted that some features of the site require a password for access. An example module is the Chemical Reactivity Hazards Instructional Module[67] developed by Robert Johnson of Unwin Co. The module can be used to motivate the importance of safety in kinetics and reaction engineering. It highlights several major incidents where uncontrolled chemical reactions can result in devastating consequences. Additional safety material is available in Crowl and Louvar's textbook.[68]

Other resources that could be used in a kinetics course include:

- *Dartmouth University has an online JAVA periodic table[69] that contains puzzles, quizzes, and a molar mass calculator. The same group has a JAVA kinetics plotter[70] that can be used to fit zero-, first-, or second-order kinetics to supplied experimental data.*
- *The University of California at Irvine has a JAVA applet to simulate molecular motion, collision, and reaction.[71] The user enters initial concentration of red, yellow, green, and blue molecules. Upon the interaction of a red and yellow molecule, green and blue molecules are formed. The reaction is reversible, and the user can enter the forward and reverse reaction rate constants.*

Laboratory experiments in kinetics and reactor design include:

- *Hesketh, et al.,[72] describe an experiment to explore the heterogeneous reaction of propane in an automobile catalytic converter. The students measure the compounds exiting the converter using Fourier transform infrared spectroscopy. Furthermore, a simple model is used to fit the experimental data to determine reaction rate parameters.*
- *Shonnard, et al.,[73] present a batch fermentation experiment to produce l-lysine in the senior laboratory. The students in the lab each perform an experiment that is part of a larger factorial design matrix. The students then share data and analyze all of the results.*
- *Li, et al.,[74] formulate an experiment to study the growth of yeast in a small-scale bioreactor. Students measure the concentration of yeast cells and glucose, and after learning about biological reaction kinetics, they estimate the doubling time for the yeast.*
- *Dahm, et al.,[75] outline a set of micromixing experiments to use in the undergraduate reaction engineering course. In a lecture on micromixing, the students are taught about the perfectly mixed and totally segregated reactor models. Experiments are performed on a system with parallel competitive reactions in a 2 L reactor with baffles and a mixer, and also in a 600 mL beaker with a magnetic stir bar. Results show that the selectivity is higher in the baffled reactor.*
- *Rice, et al.,[76] describe an experiment for propane hydrogenolysis on an alumina-supported platinum catalyst. Students run the reactor to obtain power law kinetic parameters (to determine reaction order in propane and hydrogen) as well as Arrhenius parameters.*

Trouble Spots

Trouble spots for this course include:

- *Although kinetics and reaction engineering courses are typically not as math-intensive as, say, transport phenomena, weak math skills may prevent students from carrying out solutions to determine concentration as a function of time for complex kinetics, analysis of axial dispersion in reactors, etc. Repetition through homework assignments can reinforce these concepts and build student confidence prior to exams.*
- *Students may have difficulty recalling material from previous courses that may be considered prerequisites for the kinetics and reaction engineering course. Recalling fundamental chemistry, especially organic chemistry, can be difficult for even advanced students. The instructor can summarize some of the important reactions to aid students in feeling comfortable in an upper-level course.*
- *Students often do not know order-of-magnitude values for reactor volumes or pressure drops. The instructor can provide them with general values on a handout they can paste in the front of their textbook. For an example see Reference 54 or the books by Woods[55] or Fogler.[56]*
- *Students do not know many of the assumptions in the basic reactor models (batch, continuous stirred tank reactor, plug flow reactor) and how valid they are in laboratory or industrial applications. The instructor can demonstrate or assign problems utilizing CFD[60-62] to illustrate batch / CSTR reactors with dead zones, bypassing, poor mixing, and strong concentration gradients or illustrate plug flow reactors with axial dispersion, poor packing, etc.*

Author Experiences

At Michigan Technological University, efforts have been made to bring computer technology and hands-on problems into the Kinetics and Reactor Design course.

- *Students are asked to use COMSOL Multiphysics to solve problems involving diffusion and reaction in catalyst pellets.[31]*
- *Students are asked to write their own computer programs to simulate temporal evolutions in species concentration and temperature profiles.[63]*
- *An extra emphasis is placed on chemical reactivity and reactor safety.[62]*
- *Students are given experimental data from a laboratory course and are asked to use it to predict reaction rates and rate constants.*
- *The assumptions behind different reactor models are continuously emphasized. Efforts are also made to introduce non-ideal reactor models, and the advantages and disadvantages of using these models are also stressed.[75]*

PROCESS CONTROL

This course tends to stand alone in the chemical engineering curriculum, seeming to students (and some instructors) somehow disconnected from other upper-level chemical engineering courses. Coverage normally includes mathematical modeling and dynamic simulation, Laplace transforms and transfer functions, linear dynamic responses for various inputs, controllers, instrumentation and valves, closed-loop analysis, stability analysis, controller tuning, frequency response, and advanced control strategies.

Best Practices / New Ideas

Of all the courses in the chemical engineering curriculum, this one may have the most variability in how it is taught. Prior to discussing teaching methods, various approaches to course content will be discussed.

A recent article published by the International Society of Automation magazine *InTech* reported on the views of prominent chemical engineers regarding the role of process control instruction.[77]

- *Douglas Cooper (University of Connecticut, Control Station,[78] and ControlGuru.com[79]) suggests that the course provide a "practical skill set... including enough theory to excite those destined for graduate study."*
- *Cecil Smith (formerly of LSU and currently a consultant) states, "We teach fundamental principles, but include only theory relevant to engineering practice," and "Focus on basic regulatory control, and do it well. Leave optimization, model predictive control, etc., to subsequent courses and advanced-degree programs."*
- *Jim Riggs (Texas Tech and author of* Chemical and Bio-Process Control*[80]) states, "This is the classic question of theory vs. practice in engineering education. The key to this problem is to provide control courses that provide basic industrially relevant skills while also providing a fundamental understanding of process control and process dynamics."*

Riggs also states[77] that the course should teach students to:

- *Understand the unique characteristics of proportional, integral, and derivative control action; the concept of stability; and the difference between linear and nonlinear systems.*
- *Troubleshoot control loops, tune control loops, and make basic control design decisions.*

There is continuing debate over whether or not to use the Laplace domain, or to remain in the time domain. Furthermore, the utility of frequency response methods often results in similar debates among members of academia and industry.

Tom Edgar (University of Texas at Austin and co-author of the textbook *Process Dynamics and Control*) suggests[81]:

- *De-emphasize frequency response, but keep Laplace transforms.*
- *Reduce coverage of multiple approaches for PID controller tuning.*
- *Increase use of simulation in sophomore and junior courses.*
- *Introduce a number of short laboratory experiences.*
- *Use case studies to show how process control can solve real engineering problems.*
- *Teach process control in the senior year.*

A thorough discussion by authors of several process control textbooks about what to teach in process control was recently published.[82]

Once the decision of what to teach has been made by your program, preferably in conjunction with feedback from the employers of your graduates, the task of choosing how to teach the course begins. There seems to be general agreement that a combination of experiment and simulation will help students move from theory to application. In some cases, it may make more sense to move from application to general theory. If this inductive approach is taken, some suggestions can be found in the literature:

- *Moor and Piergiovanni[83] describe the use of small modular kits and Control Station.*
- *Silverstein[84] uses unit operations laboratory-scale apparatus and MATLAB/Simulink.*
- *Henry[85] demonstrates simulation and remote experiments on batch distillation.*

Additional laboratory ideas include:

- *Young, et al.,[86] describe a nonlinear, MIMO salt-mixing process control laboratory experiment.*
- *Rusli, et al.,[87] demonstrate the use of multivariable control for a quadruple-tank process control experiment.*
- *Long, et al.,[88] suggest experiments on air-pressure tank systems.*
- *Muske[89] uses a simple tank in a process control laboratory.*

Web resources include:

- *McMaster University[90, 91] hosts a web page including numerous resources for teaching controls.*
- *Henry[92] has a number of remote laboratories available online.*

Software resources include:

- *Loop-Pro Trainer (formerly known as Control Station)[93]*
- *MATLAB with Simulink,[94] a modeling interface that uses the same block notation used in most texts*
- *A numerical approach with Microsoft Excel®[95]*
- *Excel/VBA based simulation[96]*

Trouble Spots

Trouble spots for this course can include:

- *Application of dynamic mass and energy balances. This may not have been covered much in prior courses, so a detailed review of a relevant problem like a step response for heated tanks in series may be appropriate.*
- *Not understanding the physical meaning of the Laplace variable "s". Despite faculty efforts, this concept will likely remain a mystery to most students. Instead, focus on how conservation laws in the Laplace domain can be arranged to yield key information about process behaviors through parameters such as gains and time constants.*

- *Introducing computing tools too early or too late. Students must understand the how and why before actively developing models with software like Simulink.*[94] *The appropriate time to introduce them will depend on your curriculum, but probably should be after students have mastered modeling fundamentals and can at least handle simple Laplace domain solutions for open- and closed-loop systems by hand. Some simulation tools, like Loop-Pro,*[93] *can be used for inductive instruction on principles of control without requiring significant mathematical analysis.*
- *Losing sight of practical control. Better control can always be obtained—at a cost. Students must continually be reminded that there is always an optimal level of control, dependent on the cost to implement control vs. marginal profit from enhanced control. The roles of safety, security, and environmental protection should also be considered.*

Author Experiences

At the University of Kentucky, the emphasis of recent changes in the course has been to bring inductive laboratory and simulation experiences into the course.[84] The first meeting of the course brings students down to the lab to observe principles of process control where they act as the controller. They turn knobs and flip switches to control flow, pressure, and level, and gain experience that serves as a foundation for discussions of principles of process control. Other approaches adopted include:

- *Use of Simulink after students have completed a module on modeling and Laplace transformation. Using simulators from the start of the course had discouraged students from developing an understanding of what the simulators were doing, treating them as a "black box."*
- *Use of other simulators (VBA,*[96] *Loop-Pro*[93]*) to allow students to explore control concepts. The simulators are far less time-consuming and more flexible than laboratory counterparts.*
- *Emphasis on practical control following the modeling module, with particular focus on the economic constraints on control. Students are frequently asked to consider what investment in hardware and what recurring maintenance costs would be required to implement a control scheme, and then consider whether the marginal improvement results in sufficient marginal profit to justify the project.*
- *Assigning a role in an industrial project to reduce energy costs in a process at a local specialty chemical plant. Students work across multiple courses (including teams with underclassmen) to solve a real industrial problem.*[97]
- *Requiring students to work with technology students at another institution to perform a detailed design of a control system.*[98]

SENIOR DESIGN

The senior or "capstone" design course can be intimidating to some faculty. In many departments the course was traditionally taught by a retired industrial practitioner who had a good idea of the types of deliverables that were representative of what students would encounter in the workplace, but this may not be the case today. In addition, the advent of process simulators in the 1970s and 1980s has had a huge impact on the way that senior design is taught. The senior design course typically includes both traditional lecture content as well as a capstone project. Academic content typically includes flowsheet synthesis and development, process simulation, process economics, and equipment design/heuristics. Depending on the background of the instructor and whether the course is one or two semesters, a laundry list of additional topics might include sustainability and "green design" concepts,[99] process safety,[100] Good Manufacturing Practice, Six Sigma,[101] optimization,[102] selecting materials of construction, reading P&ID's, heat exchanger network or reactor network synthesis, environmental regulations, engineering ethics, batch scheduling, and product design.[103] Senior design is also the last opportunity to reinforce "soft skills" such as teamwork[104, 105] and communication.[106, 107] Furthermore, the AIChE Centennial Conference has a session on design featuring many of the design textbook authors. Videos of these talks are available online.[7]

Best Practices/New Ideas

Whether the course is one semester or two will significantly impact how the course is organized, the content that can be covered, and the scope of the design project. According to a recent survey conducted by John Wiley based on a response from 50 departments, U.S. chemical engineering departments are split down the middle—half teach one design course, and half teach a two-semester design sequence.[108]

Instructors have several challenges related to the structure and organization of the course:

- *Departments that teach one design course must be very selective and choose which content is most important for their graduates. Design projects for a one-semester offering might be best structured as multiple smaller problems that reinforce the course content being covered. Departments that teach two design courses have more flexibility to cover additional specialized content, present information on product design as well as process design, invite guest speakers, and pose design projects that stretch over an entire year.*
- *Coming up with new projects each year can be a challenge for instructors. Starting early is important since it may take some time to define prospective projects and mentors. In addition to gleaning ideas from the literature (discussed below), solicit departmental faculty at the end of the spring semester or in the summer to generate some ideas. Contact enrolled students early in the summer and invite them to define their own project subject to some constraints on what the project should include. If your campus has an Engineering Entrepreneurship class,*[109, 110] *partner with them to include your students.*
- *Industrial partners, especially if the department is located near industry or research organizations, can serve as sources of design projects and mentors. The local AIChE section could be a good resource for local practitioners who would be willing to participate. Industrial alumni*

who have been through the course can be excellent mentors because they are familiar with the deliverables required. In addition, industrial advisory boards may be helpful in identifying key skills expected for new employees, which may help define course content.

- *Additional project advisors may be needed depending on the class size and the instructor's background. Some departments enlist all faculty to propose and sponsor one design project each year. Other sources of mentors include faculty in other related departments (*e.g.*, Materials Science, Food Science, Environmental Engineering, or Computer Science); this is especially effective if the students are double majors in that department.*
- *If students are working on projects that require experimental work or small-scale construction, funding can be an issue. Most departments have funds available for laboratory equipment and supplies, but funding levels for design must be considered when proposing and defining the scope of projects. Some departments ask companies to sponsor projects for a flat fee (*e.g.*, $5,000) or the cost of materials. Industrial advisory board members/companies or alumni may be additional sources for senior design funds.*
- *Depending on the deliverables, the learning outcomes, and the number of mentors involved, assessment can be a challenge. Approaches to this issue are discussed by Baker, et al.,[111] Rogge, et al.,[112] and Davis, et al.[113]*
- *Addition of new material may be necessary. One example is solids processing, which is common in chemical engineering practice, but is not usually covered extensively in the curriculum. Good references are available from Davey and Garside,[114] Rhodes,[115] Wibowo and Ng,[116] and Hill and Ng.[117]*

Examples of design projects:

- *The text by Turton, et al.,[118] contains six complete senior design projects in addition to the extensive list of projects on their website.[119] Shaeiwitz and Turton[120] describe two examples of novel capstone design projects: an ice cream manufacturing process and the design of a transdermal drug delivery patch. In addition, they have developed additional product design projects.[121]*
- *The text by Peters, et al.,[122] includes problem descriptions for five major projects, five minor design problems, and seven practice-session problems.*
- *Weiss and Castaldi[123] describe a tire gasification senior design project that integrates laboratory experiments and computer simulation.*
- *Benyahia[124] outlines a project involving vinyl chloride monomer (VCM), emphasizing its compliance with ABET 2000 criteria.*
- *Hernandez, et al.,[125] present a biodiesel design project that highlights the potential contributions of chemical engineering to areas such as new energy sources, global warming, and environmental sustainability.*

AIChE National Student Design Competition problems are also available each year in the fall to department chairs and student chapter advisors. They may be completed by students over the course of 30 days any time during the year (if they choose to enter their report into the competition). An archive of past problems and solutions is available from AIChE.

Examples of additional ideas for course content and structure:

- *Organizations such as AIChE,[126] the World Congress of Chemical Engineering,[127] and NASA[128] sponsor annual design competitions. Kundu and Fowler[129] discuss the use of engineering design competitions to engage students. Often these involve the use of multidisciplinary teams, which is discussed by Redekopp.[130]*
- *Silverstein[131] and Hadley[132] describe the use of wikis in senior design as a project-management tool.*

Web resources:

- *Cadwell, et al.,[133] feature a series of short online videos on "Topics in Engineering Design" that include communication in design, design considerations, the design process, and patents and literature.*
- *The On-Line Ethics Center at the National Academy of Engineering,[134] the Markkula Center for Applied Ethics,[135] and the Center for the Study of Ethics in Society[136] have websites with case studies and other materials for teaching engineering ethics.*
- *As described earlier, process safety modules are available through the Safety and Chemical Engineering Education (SACHE) program.[66]*
- *The EPA makes available exposure assessment tools and models.[137]*
- *Miller[138] has posted a set of slides on cost estimation.*
- *Milligan[139] hosts a website with specific process equipment costs estimates.*
- *UT Austin[140] lists helpful reference books, periodicals, and trade journals as resources for chemical pricing.*

Software resources:

- *Process simulators typically used in senior design include Aspen Dynamics, Aspen HYSYS, Aspen Plus, Aspen Batch Process Developer (formerly Batch Plus), CHEMCAD, PRO/II, SuperPro Designer, and UNISIM.*
- *The Aspen academic suite has several new modules. Aspen Process Economic Analyzer (formerly Icarus Process Evaluator) can be used for interactive equipment sizing as well as estimation of purchase costs and total investment. The package now includes modules for adsorption and batch distillation.[141]*
- *The text and website by Seider, et al.,[108] include self-study examples and multimedia instruction, focusing on Aspen Plus and HYSYS.*

Trouble Spots

Trouble spots for this course can include:

- *Team Dynamics: Although most students have worked in groups during unit operations lab or in homework groups, senior design is by far the biggest group project that many of them have tackled. Instructors should require design teams to define team expectations, roles, and responsibilities early in the semester. Providing instruction or resources on the phases of team performance, personality types,[142] and learning styles[143] can alleviate potential* *problems. An additional suggestion of Sauer and Arce[144] is that teams get together and, as their first task, develop an "Agreement of Cooperation." This agreement will serve as the bylaws of the team and can only be changed with a majority vote of the team members. Administering a peer evaluation tool is essential since much of the course grade will depend on the group project. Instructors might also consider a mechanism that reflects individual contribution; for example, students could be required to keep a design notebook[145] or submit their individual written contributions. This can be helpful if there is dissent within the team about an individual's contribution.*

- *Writing and Speaking Deliverables: The senior design report is likely the most formal and the longest document that students will produce. Even if students have taken a technical writing course, many are overwhelmed and do not feel confident about structure, format, and citation details. Some campuses have Writing and Speaking Centers on campus or in-house technical writing consultants who can assist by providing resources, giving a class lecture, or even reviewing student work. Allowing groups to submit a draft to the instructor a week in advance for a review can identify major problems while still allowing time for correction.*
- *Originality of student writing: Design instructors may want to use software such as turnitin.com[146] (or suggest it to students) to avoid plagiarism issues.*
- *Student procrastination: The combination of "senioritis" and procrastination can result in students trying to cram in months of works into weeks or days. Instructors can help students pace themselves by structuring the project into deliverables that are spread over the one or two semesters. For example, in a two-semester sequence in which the projects are assigned in October, students could produce a literature review/technical background in November, a status report in February, an oral presentation in March, and the final report and poster in April. Design teams should submit a project schedule and work plan early on as one of the deliverables. Some instructors require students to produce progress reports in memo form periodically during the duration of the project. Finally, depending on the size of the class, the instructor could meet with each team or each project manager regularly throughout the semester to hold them accountable.*

Author Experiences

At North Carolina State University senior design is taught as a two-semester sequence. The first semester is a more traditional lecture-style class with instructional design content, with students being assigned to teams early in the fall semester and beginning work on their design project, which carries into the spring semester. The spring is focused primarily on the project, with classroom time being devoted to guest lectures that address topics relevant to professional development. Additionally, the author has incorporated the following in the Senior Design course:

- *Guest speakers, in particular successful alumni, address professional development topics, career paths, and non-traditional careers such as medicine, law, pharmacy, business, teaching, or entrepreneurship. Financial planning, business and electronic etiquette, and professional dress are issues that students will soon face. Alumni panels on "Making the Transition from Student to Employee," "Changing Jobs," and "Graduate School" can be a very effective way to address these issues.*
- *The traditional oral presentation can be moved to mid-semester as a status update; this enables advisors to provide feedback that can be incorporated prior to the final report. The author holds an end-of-semester poster session and invites students' parents, the Industrial Advisory Board members, and current junior students. Starting off with a 2-minute summary of each project and then adjourning to a 60- or 90-minute poster session can be an effective way of having students present their work and creates a celebratory environment instead of the high stakes formal presentation. Parent response to this type of event is typically very positive; it may be the first time they have been invited to participate in an event at the university involving their student. This also gives rising seniors an opportunity to see what is required for a senior capstone project. Giving awards for "best in show" recognizes those students who make exceptional effort and helps rising seniors see where the bar is set.*
- *CATME[147, 148] is an easy-to-use online tool that collects and analyzes self and peer evaluations of team members' contributions. The peer-evaluation instrument is administered with each major deliverable, and team members receive feedback on their individual performance compared to the group average after each submission. Any low-performing students are identified by the instructor, and the team meets with the instructor to discuss the issue so that it can be addressed early. Final peer evaluations are submitted one week before the end of the semester to allow time for rebuttal if necessary.*
- *The author provides instruction or resources in technical writing, oral presentations, and how/when to cite.[149, 150] In addition, students are provided with exemplary documents from a previous year that demonstrate expectations.*
- *The text by Turton, et al.,[118] contains a CD-ROM with the latest version of CAPCOST, a tool for evaluating fixed capital investment, full process economics, and profitability—now expanded with cost data for conveyors, crystallizers, dryers, dust collectors, filters, mixers, reactors, and screens. It also contains the HENSAD tool for constructing temperature-interval, cascade, and temperature-enthalpy diagrams; estimating optimal approach temperatures; and designing heat exchanger networks.*
- *The Thomas Register[151] is a useful database for equipment vendors.*
- *Bullard, et al.,[152] provide three web-based case studies in the area of biomanufacturing for the production of co-protein, citric acid, and ammonia. Supporting materials have been developed for each case study, including a problem statement, an exemplary solution, and a summary of the difficulties and typical errors that might be encountered.*

CONCLUSIONS

This paper has described some of the best practices for use in the following chemical engineering courses that traditionally occur later in the curriculum: solution thermodynamics; heat and mass transfer; kinetics and reactor design; process control; and senior design. A common thread is in the deviation from the traditional lecture format. When this is done, the students are given the opportunity to take ownership of their own learning. Popular methods include the use of in-class demonstrations, hands-on activities, tours of the unit operations lab, and seeing a movie or simulation of a concept. Additionally, the softer skills of engineering are finding their way into the classroom, with the most popular ones being an increased emphasis on communication and teamwork skills.

It has been our collective experience that incorporating novel methods into the classroom can increase learning as students in the latter part of the curriculum transition from the classroom to the workplace or graduate school. Interestingly enough, the addition of many of these novel methods does not require a significant amount of effort, yet there may be considerable benefit for the students involved.

It can be overwhelming to consider substantial changes to an established course, but an approach that has worked for the authors is to start with a course that we have taught before. We first identify a handful of new ideas to bring into the classroom for the next time we teach the course. As we implement them, we will ask for informal feedback from students. This will often be reinforced through the formal course evaluations. Then, the next time the course is taught, we make modifications as we see fit. After a few years, the course may look totally different from the original course offering.

For copies of the presentation slides from the Summer School, contact one of the authors.

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