



chemical engineering education

VOLUME 42

• NUMBER 4

• FALL 2008



Chemical Engineering Division, American Society for Engineering Education

American Institute of Chemical Engineers



- The 10 Worst Teaching Mistakes I. Mistakes 5–10 (p. 201)
Felder, Brent
- Advisors Who Rock: An Approach to Academic Counseling (p. 218)
Bullard
- The Hydrodynamic Stability of a Fluid-Particle Flow: Instabilities in Gas-Fluidized Beds (p. 179)
Liu, Howley, Johri, Glasser
- Quick and Easy Rate Equations for Multistep Reactions (p. 211)
Savage
- Lab-on-a-Chip Design-Build Project with a Nanotechnology Component
in a Freshman Engineering Course (p. 185)
Allam, Tomasko, Trott, Schlosser, Yang, Wilson, Merrill
- A Module to Foster Engineering Creativity: an Interpolative Design Problem and
an Extrapolative Research Project (p. 166)
Forbes
- Introduction to Studies in Granular Mixing (p. 173)
Llusa, Muzzio
- Interdisciplinary Learning for ChE Students from Organic Chemistry Synthesis Lab
to Reactor Design to Separation (p. 193)
Armstrong, Comitz, Biaglow, Lachance, Sloop
- Pedagogical Training and Research in Engineering Education (p. 203)
Wankat

Author Guidelines for the LABORATORY Feature

The laboratory experience in chemical engineering education has long been an integral part of our curricula. CEE encourages the submission of manuscripts describing innovations in the laboratory ranging from large-scale unit operations experiments to demonstrations appropriate for the classroom. The following guidelines are offered to assist authors in the preparation of manuscripts that are informative to our readership. These are only suggestions, based on the comments of previous reviewers; authors should use their own judgment in presenting their experiences. A set of general guidelines and advice to the author can be found at our Web site: <<http://che.ufl.edu/~cee/>>.

- c Manuscripts should describe the results of original and laboratory-tested ideas. The ideas should be broadly applicable and described in sufficient detail to allow and motivate others to adapt the ideas to their own curricula. It is noted that the readership of CEE is largely faculty and instructors. Manuscripts must contain an abstract and often include an Introduction, Laboratory Description, Data Analysis, Summary of Experiences, Conclusions, and References.
 - An Introduction should establish the context of the laboratory experience (e.g., relation to curriculum, review of literature), state the learning objectives, and describe the rationale and approach.
 - The Laboratory Description section should describe the experiment in sufficient detail to allow the reader to judge the scope of effort required to implement a similar experiment on his or her campus. Schematic diagrams or photos, cost information, and references to previous publications and Web sites, etc., are usually of benefit. Issues related to safety should be addressed as well as any special operating procedures.
 - If appropriate, a Data Analysis section should be included that concisely describes the method of data analysis. Recognizing that the audience is primarily faculty, the description of the underlying theory should be referenced or brief. The purpose of this section is to communicate to the reader specific student-learning opportunities (e.g., treatment of reaction-rate data in a temperature range that includes two mechanisms).
 - The purpose of the Summary of Experiences section is to convey the results of laboratory or classroom testing. The section can enumerate, for example, best practices, pitfalls, student survey results, or anecdotal material.
 - A concise statement of the Conclusions (as opposed to a summary) of your experiences should be the last section of the paper prior to listing References.

EDITORIAL AND BUSINESS ADDRESS:

Chemical Engineering Education
Department of Chemical Engineering
University of Florida • Gainesville, FL 32611
PHONE and FAX : 352-392-0861
e-mail: cee@che.ufl.edu

EDITOR

Tim Anderson

ASSOCIATE EDITOR

Phillip C. Wankat

MANAGING EDITOR

Lynn Heasley

PROBLEM EDITOR

James O. Wilkes, U. Michigan

LEARNING IN INDUSTRY EDITOR

William J. Koros, Georgia Institute of Technology

PUBLICATIONS BOARD

• **CHAIRMAN** •

John P. O'Connell
University of Virginia

• **VICE CHAIRMAN** •

C. Stewart Slater
Rowan University

• **MEMBERS** •

Kristi Anseth
University of Colorado

Jennifer Curtis
University of Florida

Rob Davis
University of Colorado

Pablo Debenedetti
Princeton University

Dianne Dorland
Rowan

Thomas F. Edgar
University of Texas at Austin

Stephanie Farrell
Rowan University

Richard M. Felder
North Carolina State University

H. Scott Fogler
University of Michigan

Jim Henry
University of Tennessee, Chattanooga

Jason Keith
Michigan Technological University

Steve LeBlanc
University of Toledo

Ron Miller
Colorado School of Mines

Susan Montgomery
University of Michigan

Lorenzo Saliceti
University of Puerto Rico

Stan Sandler
University of Delaware

Donald R. Woods
McMaster University

Chemical Engineering Education

Volume 42

Number 4

Fall 2008

► **RANDOM THOUGHTS**

201 The 10 Worst Teaching Mistakes

I. Mistakes 5–10

Richard M. Felder and Rebecca Brent

► **ADVISING**

218 Advisors Who Rock: An Approach
to Academic Counseling

Lisa G. Bullard

► **CURRICULUM**

179 The Hydrodynamic Stability of a Fluid-Particle Flow: Instabilities
in Gas-Fluidized Beds

Xue Liu, Maureen A. Howley, Jayati Johri,

and Benjamin J. Glasser

211 Quick and Easy Rate Equations for Multistep Reactions

Phillip E. Savage

185 Lab-on-a-Chip Design-Build Project with a Nanotechnology
Component in a Freshman Engineering Course

Yosef Allam, David L. Tomasko, Bruce Trott, Phil Schlosser,

Yong Yang, Tiffany M. Wilson, and John Merrill

► **CLASSROOM**

166 A Module to Foster Engineering Creativity: an Interpolative
Design Problem and an Extrapolative Research Project

Neil S. Forbes

173 Introduction to Studies in Granular Mixing

Marcos Llusa and Fernando Muzzio

193 Interdisciplinary Learning for ChE Students from Organic
Chemistry Synthesis Lab to Reactor Design to Separation

Matt Armstrong, Richard L. Comitz, Andrew Biaglow,

Russ Lachance, and Joseph Sloop

► **EDUCATIONAL RESEARCH**

203 Pedagogical Training and Research in Engineering Education

Phillip C. Wankat

CHEMICAL ENGINEERING EDUCATION (ISSN 0009-2479) is published quarterly by the Chemical Engineering Division, American Society for Engineering Education, and is edited at the University of Florida. Correspondence regarding editorial matter, circulation, and changes of address should be sent to CEE, Chemical Engineering Department, University of Florida, Gainesville, FL 32611-6005. Copyright © 2008 by the Chemical Engineering Division, American Society for Engineering Education. The statements and opinions expressed in this periodical are those of the writers and not necessarily those of the ChE Division, ASEE, which body assumes no responsibility for them. Defective copies replaced if notified within 120 days of publication. Write for information on subscription costs and for back copy costs and availability. POSTMASTER: Send address changes to Chemical Engineering Education, Chemical Engineering Department, University of Florida, Gainesville, FL 32611-6005. Periodicals Postage Paid at Gainesville, Florida, and additional post offices (USPS 101900).

A MODULE TO FOSTER ENGINEERING CREATIVITY: *an Interpolative Design Problem and an Extrapolative Research Project*

NEIL S. FORBES

University of Massachusetts, Amherst • Amherst, Massachusetts 01003

Teaching techniques that enhance creativity are as critical as teaching technical skills. Innovation, the result of the creative process, is necessary for technological advancement and is highly correlated with economic prosperity and success.^[1, 2] While creativity and innovation play a role in most aspects of engineering, they are rarely discussed explicitly in engineering courses. Engineers typically receive instruction in scientific principles and their conceptual application, but seldom do they receive formal instruction in creative problem solving.^[3-5] It is particularly important to focus on creativity in introductory engineering courses to retain independent thinkers who tend to leave university earlier than others.^[6] In addition, tools that enhance creativity are necessary because of increased employment in the life sciences and a general expansion in career opportunities for chemical engineers.^[7-12] Creativity skills enable engineers to learn new material faster and improve interactions with colleagues in other disciplines.

Throughout my teaching experience I have been asked by many students how they can improve their creativity and problem-solving skills. From these experiences, I have noticed that many students limit their creative potential by censoring their ideas before fully investigating them. Encouraging students to pursue ideas regardless of how outlandish the ideas appear produces more vibrant, diverse, and ultimately useful output. Formalization of this instruction process will benefit a greater population of students than individual interactions alone.

Engineering creativity can be broken down into two distinct steps: idea generation and idea analysis. Success with creativity depends on the number of ideas formed and the ability to perform these two steps separately.^[4, 13-15] Generating a large number of ideas, regardless of their quality, increases the likelihood that an innovative concept will be discovered.^[13-16] Students who struggle with open-ended problems often try to combine idea analysis and generation.

Analysis requires contradictory thought processes that can poison self-confidence and tolerance of risk, which are necessary for idea generation. During the brainstorming step, overly critical analysis limits the formation of the random and disparate connections that are needed to generate long lists of potential ideas, which often leads to abandonment of the most tangential and innovative ideas.

Here I describe a teaching module that can be integrated into an introductory chemical engineering course to maximize students' creative potential. This module builds upon previous efforts that have shown that creativity can be taught in the classroom.^[1, 15, 17] This module includes an exercise to illustrate engineering creativity, an open-ended research project, and a questionnaire to assess individual creativity. The material that describes the role of creativity in engineering can typically be described in one or two lectures.

IDEA GENERATION

Idea generation is a highly personal process that varies greatly from person to person. Many techniques have been described to explain the workings of this process,^[4, 13, 15, 18] including brainstorming,^[19, 20] synectics,^[21, 22] and lateral thinking.^[23, 24] Creativity in engineering is dependent on many

Neil Forbes is an assistant professor in the Department of Chemical Engineering at the University of Massachusetts, Amherst. He has an adjunct appointment in the Molecular and Cell Biology Program and at the Pioneer Valley Life Sciences Institute. He received his Ph.D. in chemical engineering from the University of California, Berkeley, and was a postdoctoral fellow in radiation oncology at Harvard Medical School. His education interests are in introductory engineering education and the integration of life-science material into the chemical engineering curriculum. His research interests include drug delivery, tumor biology, and bacterial anti-cancer therapies.



© Copyright ChE Division of ASEE 2008

factors, including innate ability, experience, and good mental habits.^[15, 16] While some students have more innate ability and experience from which to draw, many students fall into mental traps that limit their creative potential. Reading and exposure to experiences outside of engineering often enhances creativity.^[25] A creative environment encourages independent thinking, self-awareness, openness to experience, and breadth of vision.^[6, 18]

When struggling to generate novel ideas, students should be encouraged to use their own personal experiences. The most creative ideas often come from students who can effectively use their personal experiences and knowledge base. For example, a foreign student in a bioprocess engineering course I taught in 2003 had worked previously in a laboratory studying gene therapy. She was from a tropical country and had a family that had been painfully affected by malaria. Putting these two experiences together, she came up with an idea to manipulate the sickle cell gene to provide protection against malaria. Similar ideas could not be found in the literature, and this approach has therapeutic promise. This example illustrates how connecting personal experience (malaria) with educational knowledge (gene therapy) can lead to innovation.

EXTRAPOLATIVE VS. INTERPOLATIVE PROBLEMS

To help students with open-ended tasks I suggest that creative problems be divided into two distinct modes: extrapolative and interpolative. These two modes are defined by how the goals of the problem relate to known facts. Interpolative creativity is the creation of connections between known facts to arrive at clearly defined goals. Extrapolative creativity is the creation of new ideas as an outgrowth from known facts toward more loosely defined goals. For example, mass and energy balance problems require interpolative creativity; research papers predominately require extrapolative creativity; and process design requires elements of both. Typically, engineering students prefer interpolative problems. Both types of problems, however, require the generation of many high-quality ideas and the confidence to generate them. Understanding the similarity of the tools needed to address these two modes will enhance students' ability with open-ended problems.

Classic examples of problems that require interpolative creativity are the mass balance problems encountered in introductory chemical engineering courses (Figure 1). Problems of this type require small creative steps when drawing system boundaries. For the example in Figure 1, three different choices are possible: around unit A, around unit B, and an overall balance. More complex problems would have more possibilities, with some being difficult to identify on first observation. Many students start such a problem by writing mass balance equations around unit A before conceptualizing all possible system boundaries. In doing so, they miss that an

overall balance is necessary to solve the problem. Generating a list of possible boundaries (ideas) before analyzing them would help students solve these problems more efficiently.

A research paper is good example of an extrapolative creativity problem that students often encounter. When assigned extrapolative problems, students should use similar techniques to generate ideas as they do with interpolative problems. Idea generation is complicated for open-ended problems by the "fear of a blank page" that leaves students not knowing where to start. As with interpolative problems, practice generating disparate ideas before evaluating them can help with the extrapolative creative process. Different from interpolative problems, loosely defined goals can make the brainstorming space seem limitless. To overcome this apparent limitlessness, students should be encouraged to use their previous experience and prior knowledge to redefine the goals of the assignment. They should especially be encouraged to use those experiences outside of engineering. For example, a student struggling to find a subject for a research paper (as described in detail below) found a clever topic by exploring his hobbies. This student was an avid bicyclist who had recently paid too much for a high-end bicycle. He chose to write a paper about ways to improve the production of titanium and reduce its cost, which turned out to be a well-defined and interesting project that the student found highly rewarding.

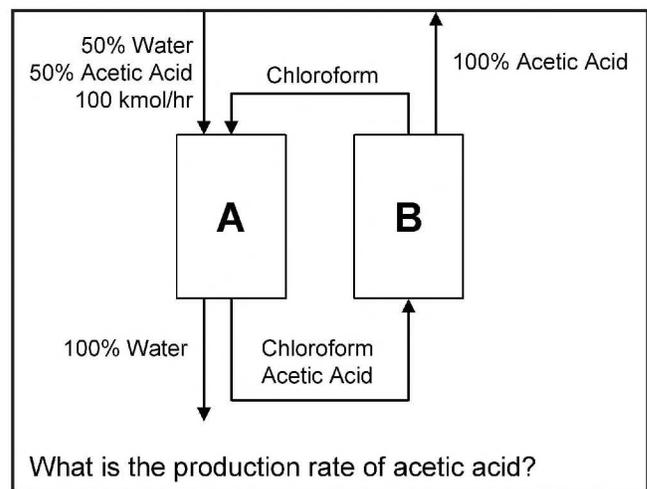


Figure 1. Simple mass balance problem to illustrate interpolative creativity. An equimolar stream of water and acetic acid is fed to a liquid-liquid exchanger (A), which partitions the acetic acid into a chloroform extract and produces an idealized pure water stream. The acetic acid is removed from the chloroform by distillation (B). Three different system boundaries can be drawn: around A, around B, and around the entire process. Without knowing the recycle rate of chloroform an entire process balance is necessary to calculate the production rate of acetic acid. Identifying many possible solutions (in this case system boundaries) is necessary to solve interpolative problems.

EXERCISE TO DEMONSTRATE ENGINEERING CREATIVITY

The following interpolative exercise is a project to design column packing material that illustrates engineering creativity. Presenting this exercise during class complements the lectures and provides a defined time period for students to practice their creativity skills. The exercise is comprised of two parts that are to be administered before and after instruction on creativity. Designing column packing is a geometric problem that has many possible solutions, is complex enough that an optimal solution cannot be ascertained on first inspection, but is simple enough to allow students to easily analyze their ideas. This exercise complements the extrapolative brainstorming problems^[5, 13] and interpolative, brain teasers^[15, 17] that have been described previously. The complexity of this problem illustrates to students how separating brainstorming and analysis can produce many distinct and effective designs.

There are currently numerous designs and shapes of column packing commercially available (Figure 2). Most of these designs were determined by a combination of experimentation, trial and error, and experience.^[26] While the shape of the packing materials significantly affects their behavior, the optimal shape cannot be determined theoretically. The best packing materials have a high surface area for mass transfer and a low resistance to gas flow.^[26, 27]

To begin the exercise the entire column packing simulation is described in detail. The overall goal of the process is to design a packing material that maximizes productivity in a packed column absorber. To make the design of packing material a tractable creativity exercise it was reduced to two dimensions. During the exercise, packing materials are designed on

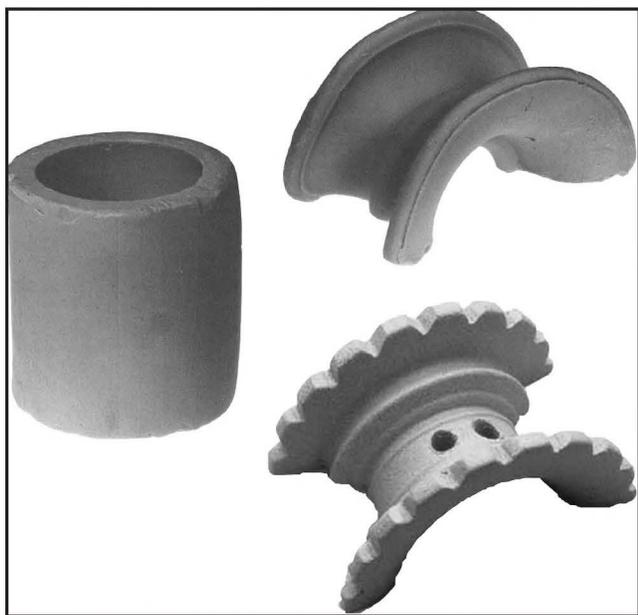


Figure 2. Examples of commercially available column packing materials.

11×11 grids and are filled into a theoretical 59×51 column using a stochastic Visual Basic simulator (Figure 3, which is available upon request). Packing designs must be physically possible, single pieces: all pixels in each design must share a border with at least one other pixel (as in Figures 2-4). The simulator fills the column by rotating the two-dimensional designs and placing them as close to the bottom of the column as possible without overlapping already packed pieces (Figure 3). Once the simulator has filled the column, it calculates the overall void fraction from the percentage of empty space and the surface area from the length of exposed edges. For simplicity, the gas flowrate and the overall production rate are assumed to be directly proportional to the void fraction. The simulator determines the performance of packing materials by multiplying the void fraction by the surface area.

As an example of packing material simulation, a solid square (Figure 3A) has a void fraction of 0.359, a surface area of 616, and a productivity of 221. It is a poor performer because it does not have much surface area. A better design would be a crossed I-bar (Figure 3B), which has a void fraction of 0.726, a surface area of 1,641, and a productivity of 1,192. These two examples demonstrate why this problem is useful for demonstrating the utility of engineering creativity. While void fraction and surface area are coupled to each other, good designs can independently increase both independently. In addition, the nonlinear relationship between these two parameters makes theoretical prediction of an optimum design difficult.

The exercise is broken into two parts. In the first part, prior to instruction on creativity, students are provided with the

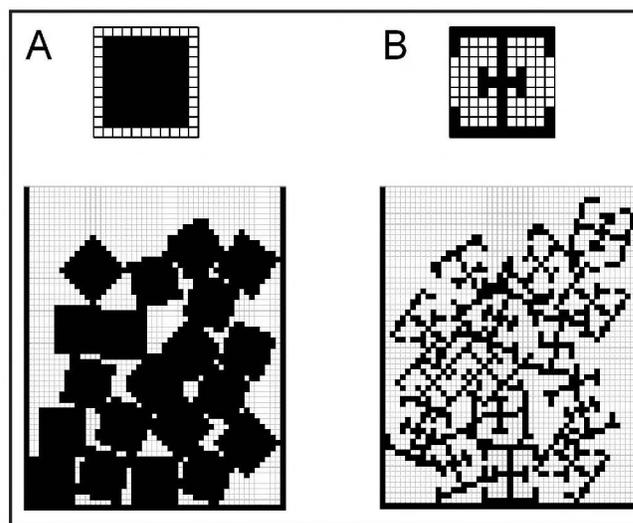


Figure 3. Two examples of packing materials filling a two-dimensional column. The solid square packing (A) is a poor performer. When packed it had a void fraction of 0.359, a surface area of 616 and an overall productivity of 221. The I-bar packing (B) is a much better performer. When packed it had a void fraction of 0.726, a surface area of 1,641 and an overall productivity of 1,192. All values are dimensionless.

packing simulator, and asked to create designs with the greatest productivity that they can in 10 minutes. During this time, students generate only a few designs with little variation. At the end of this period, students are introduced, by lecture, to the creativity techniques describe above, with emphasis on the utility of generating many disparate ideas and decoupling idea generation and analysis.

In the second part of the exercise students are provided with a handout containing a set of 11×11 grids on which to design packing materials by hand (Figure 4). Students are asked to generate as many packing designs as possible without analysis in 10 minutes. Their ideas for packing designs can be entirely disparate or can build upon each other. If the ideas build upon each other, students could provide an explanation of how it improves on previous ideas (Figure 4). Students are encouraged, however, to have as many disparate design ideas as possible, so as to add new possibilities regardless of whether productivity is improved. Creating only ideas that obviously improve productivity could potentially limit the creative process. After the 10-minute idea generation period, students return to the simulator and determine the void fraction, surface area, and productivity of each design. This second part of the exercise is intended to illustrate the benefit of generating a large number of potential designs before analysis. Students will find that while many designs perform poorly, some outlandish ideas will outperform their best ideas from the first part of the exercise. Typically, classes observe that students who have generated the most ideas also have the most productive designs.

CREATIVITY IN AN ENGINEERING RESEARCH PROJECT

Open-ended literature research projects are an excellent mechanism to illustrate extrapolative engineering creativity to introductory engineering students. This section describes a short research project in which students are asked to describe an aspect of chemical engineering that has a significant impact on society. Students can approach this broad assignment from two directions; they can either 1) describe a novel technology that could be used for societal benefit using engineering principles, or 2) describe a societal problem that could be addressed by novel chemical engineering methods. In other words, focus can be on either the technology or the societal problem. Students are encouraged to identify topics that are interesting and personally significant to them. Identifying novel and appropriate topics can be a daunting task for some student and requires considerable effort and creativity. The techniques described to enhance creativity can be especially helpful during the initial topic-identification period of this assignment.

The final paper should 1) fully describe the technology or societal problem, 2) describe how the technology addresses a problem or how the problem could be addressed with technol-

ogy, 3) describe challenges that exist in the application of the technology or the solution of the problem, and 4) cite at least three references supporting all technical claims. Because the focus of the assignment is on the generation of a novel idea, the paper can be short, about 3-5 pages. In addition, an important component of the assignment is exploration of the scientific literature. In the process of exploration students will learn how large or small their chosen fields are and how difficult it can be to generate truly novel ideas.

When first introduced, students are not given any specific guidance to help generate ideas. Many students have difficulty with this aspect of the assignment. Generating new technical ideas is a skill that students are not typically exposed to in high school education. After allowing students a few days to independently struggle with creative idea generation, the lectures and exercises described in the sections above are presented. Students are then asked to return to the task of idea generation. They are encouraged to use the literature and their personal experiences to generate as many topics as possible before evaluating them. Once a reasonable list is generated, students use the literature, peer review, and their own judgment to pick the best one. Students are told to rate their ideas based on 1) novelty, 2) scientific correctness, 3) interest, 4) potential societal benefit, 5) feasibility, and 6) testability. A good idea will also not be too large (*i.e.*, catalysis or energy) that it cannot be easily summarized or be too small that not

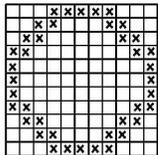
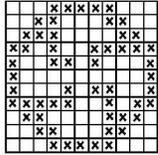
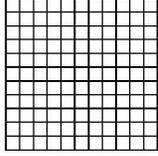
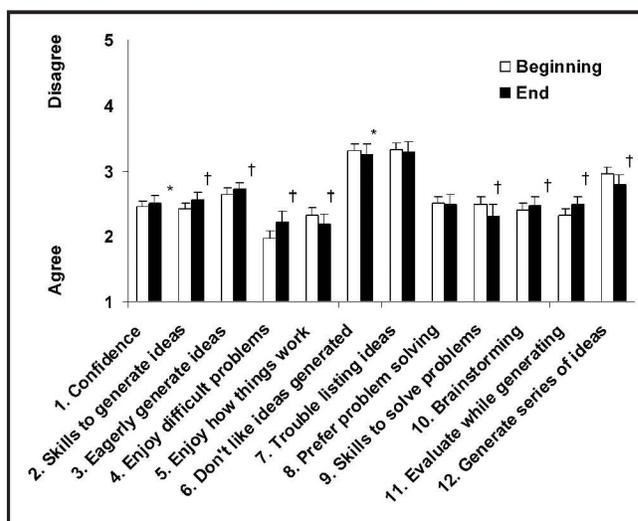
Design	Reason / Improvement
	<u>Allow better than filled</u> <hr/> <hr/> <hr/>
	<u>Baffles increase surface area</u> <hr/> <hr/> <hr/>
	<hr/> <hr/> <hr/>

Figure 4. Portion of student handout used to design two-dimensional column packing material containing two designs and brief rationales justifying them.

Figure 5. Results of creativity survey administered to first-year chemical engineering students at the University of Massachusetts in 2004 and 2005. Most differences between the beginning and end of the semester were significant (*, $P < 0.05$; †, $P < 0.01$).



enough information is available. Most students find that the challenge of generating ideas for this assignment, similar to the in-class exercise, helps foster their engineering creativity and improves the quality of their ideas.

EVALUATION OF STUDENT CREATIVITY

For two sequential years (2004 and 2005), surveys were used to evaluate student confidence with engineering creativity in the first-year chemical engineering course at the University of Massachusetts (Table 1). Students were asked to rate whether they strongly agreed (1) or strongly disagreed (5) with the twelve statements in the survey. These surveys were administered at the beginning of the semester (before any discussion of creativity) and at the end of the semester. During the semester, the materials and exercises on engineering creativity were presented. The questions were designed to ascertain students' attitude toward creativity (questions 1, 4, 5, 6, and 8), behavior when required to be creative (questions 3, 7, 11, and 12) and skills at being creative (questions 2, 9, and 10).

Between the beginning and end of both investigated semesters, 10 of the twelve student-responses changed significantly (Figure 5). For all questions, students responded positively about creativity (responses less than 3). The only questions that students disagreed with (questions 6 and 7; responses greater than 3) were worded negatively. Comparing students' responses at the beginning and end of the semester gave an indication of the effectiveness of the presented materials. Over the course of the semester (Figure 5) students gained confidence with generating ideas (question 1; $P < 0.05$), felt that they had more skills to generate ideas (question 2; $P < 0.01$), more eagerly generated ideas (question 3; $P < 0.01$), enjoyed solving difficult problems more (question 4; $P < 0.01$), liked the quality of their ideas more (question 6; $P < 0.05$), and brainstormed more

TABLE 1
Student Creativity Survey

Rate the following as best as possible:					
	strongly agree				strongly disagree
1. I feel confident developing novel ideas and concepts	1	2	3	4	5
2. Based on my previous educational experience, I feel that I have the skills necessary to generate novel ideas and concepts	1	2	3	4	5
3. When assigned an poorly defined, open-ended task I eagerly start generating ideas	1	2	3	4	5
4. I enjoy finding solutions to difficult problems	1	2	3	4	5
5. I enjoy formulating concepts to describe how things work	1	2	3	4	5
6. I have trouble generating unique ideas because I don't like the quality of the ideas I generate	1	2	3	4	5
7. I have trouble listing more than three unique ideas when faced with open-ended assignments	1	2	3	4	5
8. I prefer problem-solving to tackling open-ended tasks	1	2	3	4	5
9. Based on my previous educational experience, I feel better prepared to solve specific problems than approach open-ended tasks	1	2	3	4	5
10. I often brainstorm when finding solutions to problems	1	2	3	4	5
11. When solving problems, I evaluate ideas as I generate them	1	2	3	4	5
12. I usually generate a series of possible ideas before evaluating them	1	2	3	4	5

TABLE 2
Correlation between questions at beginning of semester^a

Question	1	2	3	4	5	6	7	8	9	10	11	12
1. Confidence												
2. Skills to generate ideas	0.70 †											
3. Eagerly generate ideas	0.36 †	0.28 *										
4. Enjoy difficult problems	0.37 †	0.35 †	0.21									
5. Enjoy how things work	0.39 †	0.37 †	0.28 †	0.71 †								
6. Don't like ideas generated	-0.30 †	-0.27 *	-0.12	-0.22 *	-0.10							
7. Trouble listing ideas	-0.23 *	-0.25 *	-0.21	-0.24 *	-0.15	0.36 †						
8. Prefer problem solving	0.04	0.11	-0.32 †	0.34 †	0.26 *	-0.08	0.09					
9. Skills to solve problems	0.12	0.08	-0.30 †	0.32 †	0.27 *	0.06	0.15	0.57 †				
10. Brainstorming	0.24 *	0.30 †	0.17	0.24 *	0.29 †	-0.01	-0.14	0.05	0.11			
11. Evaluate while generating	0.26 *	0.23 *	0.17	0.11	0.18	-0.20	-0.05	-0.01	0.00	0.34 †		
12. Generate series of ideas	0.03	-0.04	0.12	0.05	0.14	0.09	-0.10	-0.07	0.01	-0.01	-0.09	

^aElements contain the Pearson coefficient and the significance of population correlation coefficient (*, P<0.05; †, P<0.01). The sign of the Pearson coefficient indicates direct (+) and indirect (-) correlation.

TABLE 3
Correlation between questions at end of semester^a

Question	1	2	3	4	5	6	7	8	9	10	11	12
1. Confidence												
2. Skills to generate ideas	0.58 †											
3. Eagerly generate ideas	0.54 †	0.42 †										
4. Enjoy difficult problems	0.42 †	0.35 †	0.47 †									
5. Enjoy how things work	0.31 *	0.29 *	0.45 †	0.74 †								
6. Don't like ideas generated	-0.43 †	-0.32 *	-0.33 †	-0.06	0.05							
7. Trouble listing ideas	-0.52 †	-0.34 †	-0.24	-0.17	-0.09	0.59 †						
8. Prefer problem solving	0.11	0.22	-0.01	0.46 †	0.43 †	0.31 *	0.17					
9. Skills to solve problems	0.39 †	0.42 †	0.11	0.50 †	0.43 †	0.12	-0.20	0.67 †				
10. Brainstorming	0.52 †	0.39 †	0.31 *	0.46 †	0.36 †	-0.13	-0.29 *	0.28 *	0.47 †			
11. Evaluate while generating	0.28 *	0.18	0.35 †	0.35 †	0.42 †	0.00	0.10	0.43 †	0.36 †	0.36 †		
12. Generate series of ideas	0.12	0.31 *	0.10	-0.03	0.20	-0.15	-0.34 †	-0.08	0.12	0.24	-0.14	

^aElements contain the Pearson coefficient and the significance of population correlation coefficient (*, P<0.05; †, P<0.01). The sign of the Pearson coefficient indicates direct (+) and indirect (-) correlation. Shaded cells are significant in Table 3 and not in Table 2.

when solving problems (question 10; P<0.01). Students reported that they enjoyed formulating concepts to describe how things work less (question 5; P<0.01), evaluated ideas as they generated them more (question 11; P<0.01), and generated a series of ideas less (question 12; P<0.01). These three results may reflect increased student understanding about the creative process. After the lectures, they may have had a better understand about what was meant by generating ideas before evaluating them and may be more accurately reporting their behavior. Lastly, students reported that their preference

shifted from specific problems to open-ended tasks (question 9). This reflects that the creativity module was successful for those two groups of students.

Pearson correlations between the questions were calculated to determine how individual students felt about creativity and idea generation before exposure to the creativity module (Table 2). The sign of the Pearson correlation indicates direct or indirect correlation between the questions. Significance of the population correlation coefficients indicates 95% (*, P<0.05) and 99% (†, P<0.01) confidence. Many of the initial

questions were tightly correlated, indicating that students who were confident about developing ideas (question 1) felt that they had the necessary creativity skills (question 2; Q1-Q2, $P < 0.01$) and enjoyed the creative process (question 4 & 5; Q1-Q4, $P < 0.01$; Q1-Q5, $P < 0.01$). The correlations show that students who don't like the ideas they generate (question 6) have trouble listing more than three ideas (question 7; Q6-Q7, $P < 0.01$). Question 12, which asks whether students generate a series of ideas before evaluating them, was not correlated with any other question, including confidence with idea generation (question 1), liking the quality of ideas (question 6), or feeling that they have the skills for idea generation (question 2). This lack of correlation indicates that at the beginning of the course students had not been introduced to the concept of generating ideas before evaluating them.

Many more of the questions were correlated at the end of the semester than at the beginning (Table 3; shaded region). Question pairs with increased correlation indicate changes in student perception and understanding of the creative process. Students reported that generating ideas before solving them (question 12) and brainstorming (question 10) gave them skills to generate ideas (question 2; Q2-Q12, $P < 0.05$) and skills to solve open-ended problems (question 9; Q9-Q10, $P < 0.05$). These new skills helped students have confidence to develop new ideas (question 1; Q1-Q9, $P < 0.01$). Using brainstorming (question 10) and enjoying idea generation (question 6) helped students feel more comfortable with open-ended tasks (question 8; Q6-Q8, $P < 0.05$; Q8-Q10, $P < 0.05$). Importantly, students who learned to brainstorm (question 10) and generate ideas before evaluating them (question 12) had less trouble listing unique ideas when faced with open-ended assignments (question 7; Q7-Q10, $P < 0.05$; Q7-Q12, $P < 0.01$).

CONCLUSIONS

The concepts introduced in this engineering creativity module helps students become more comfortable with open-ended problems. With these tools they learn how to approach open-ended problems and how to separate idea generation from analysis. The questionnaires administered in an introductory chemical engineering course confirmed that engineering creativity can be enhanced. The surveys showed that learning how to brainstorm and generate ideas independent of analysis reduces students' difficulty with ambiguous tasks. The results also showed that practice with creative exercises increases confidence with novel idea generation. Students who brainstormed had more success with open-ended problems and students that liked their ideas more effectively generated many ideas. While creativity is difficult to teach explicitly, creating a defined space for students to practice these skills clearly enhanced their abilities.

REFERENCES

1. Sadowski, M.A., and Connolly, P.E., "Creative Thinking: The Generation of New and Occasionally Useful Ideas," *Engineering Design Graphics Journal*, **63**(1), 20-25 (1999)
2. Weiner, S.S., "Winning Technologies" and the Liberal Arts College, paper presented at the Summer Meeting of the State Association Executives Council, National Institute of Independent Colleges and Universities, Washington, DC (1984)
3. Balabanian, N., and W.R. Lepage, *Electrical Science Course for Engineering College Sophomores, Development of an Integrated Program Utilizing a Broad Range of Materials. Final Report*, report: br-5-0796 (1967)
4. Felder, R.M., "Creativity in Engineering Education," *Chem. Eng. Educ.*, **22**(3), 120-125 (1988)
5. Felder, R.M., "On Creating Creative Engineers," *Eng. Educ.*, **77**(4), 222-227 (1987)
6. Cross, K.P., *On Creativity, The Center for Research and Development in Higher Education*, University of California, Berkeley, 1-4 (1967)
7. Utterback, J., *Mastering the Dynamics of Innovation: How Companies Can Seize Opportunities in the Face of Technological Change*, Harvard Business School Press, Boston, MA (1996)
8. Rosenbloom, R., and W. Spencer, eds., *Engines of Innovation: Industrial Research at the End of an Era*, Harvard Business School Press, Boston, MA (1996)
9. Rosenberg, N., *Exploring the Black Box: Technology, Economics and History*, Cambridge University Press, Cambridge, England (1994)
10. Barabashi, S., "Managing the Growth of Technical Information," in *Technology and the Wealth of Nations*, N. Rosenberg, R. Landau, and D.C. Mowery, eds., Stanford University Press, Palo Alto, CA, 407-435 (1992)
11. Bhidé, A., *The Origin and Evolution of New Business*, Oxford University Press, Oxford (2000)
12. Wessner, C.W., ed., *Capitalizing on New Needs and New Opportunities: Government-Industry Partnerships in Biotechnology and Information Technologies*, National Academy of Sciences, Washington, DC (2001)
13. Lumsdaine, E., M. Lumsdaine, and J.W. Shelnut, *Creative Problem Solving and Engineering Design*, McGraw-Hill, Inc., New York (1999)
14. Wankat, P.C., and F.S. Oreovicz, *Teaching Engineering*, McGraw-Hill, Inc., New York (1993)
15. Christensen, J.J., "Award Lecture... Reflections on Teaching Creativity," *Chem. Eng. Educ.*, **22**(4), 170-176 (1988)
16. Fogler, H.S., and S.E. LeBlanc, *Strategies for Creative Problem Solving*, Prentice Hall PTR, Englewood Cliffs (1995)
17. Connolly, P.E., and M.A. Sadowski, "Creativity Development in a Freshman-Level Engineering Graphics Course—an Application," *Engineering Design Graphics Journal*, **63**(3), 32-39 (1999)
18. Churchill, S.W., "Can We Teach Our Students to Be Innovative?," *Chem. Eng. Educ.*, **36**(2), 116 (2002)
19. Osborne, A.F., *Your Creative Power*, Scribner, New York (1948)
20. Osborne, A.F., *Applied Imagination*, Scribner, New York (1963)
21. Gordon, W.J.J., *Synectics, the Development of Creative Capacity*, Harper and Row, Publishers, New York (1961)
22. Prince, G.M., *The Practice of Creativity: A Manual for Dynamic Group Problem-Solving*, Simon & Schuster (1972)
23. de Bono, E., *Lateral Thinking, a Textbook of Creativity*, Ward Lock Educational, London (1970)
24. de Bono, E., *Lateral Thinking*, Harper and Row, New York (1992)
25. Prausnitz, J.M., "Toward Encouraging Creativity in Students," *Chem. Eng. Educ.*, **19**(1), 22-25 (1985)
26. Perry, R.H., D.W. Green, and J.O. Maloney, *Perry's Chemical Engineers' Handbook*, 7th Ed., McGraw Hill, New York (1997)
27. King, C.J., *Separation Processes*, McGraw-Hill, Inc., New York (1980) □

INTRODUCTION TO STUDIES IN GRANULAR MIXING

MARCOS LLUSA, FERNANDO MUZZIO
Rutgers University • Piscataway, NJ 08854

A common complaint of instructors in engineering and pharmaceutical science is the lack of laboratory experiments to teach powder processing. There are, for example, educational activities to demonstrate the effect of different variables in the particle segregation phenomena.^[1, 2] Many of these activities, however, are not designed to test particles of industrial interest. It is even more rare that segregation measurements are part of a process development educational activity. Developing a pharmaceutical process, for example, involves understanding the impact of several process and material variables (*e.g.*, fill level of blender, speed of rotation, drug loading method) on the characteristics of a final blend (*e.g.*, homogeneity and segregation of minor components, flowability and density). In addition, the activity should also study the correlations among the various blend properties; for example, changes in flowability due to lubrication can hinder the dissolution of the drug. Pharmaceutical companies can benefit greatly from well-planned process development, especially when the activity can first be developed in the small scale.^[3]

In this paper, a sequence of activities provides a concise yet illustrative training exercise to introduce students (and/or

industry personnel) to some classic problems^[4] in process development for granular solids. We focus on a pharmaceutical example where the mixing operation is expected to yield a blend with specific drug and lubricant homogeneity. Events



Marcos Llusa joined the Chemical Engineering Department at Rutgers University under the Fulbright program. There, he completed his M.S. and his Ph.D., and now holds a post-doctoral research position. He has a B.S. in chemical engineering from the National University of Rio Cuarto, Argentina.

Fernando Muzzio is the director of the new National Science Foundation Engineering Research Center on Structured Organic Particulate Systems. The center focuses on pharmaceutical product and process design. The FDA and 30 companies are currently partners. Professor Muzzio is a professor of chemical engineering at Rutgers University. For the last 15 years, pharmaceutical product and process design has been Professor Muzzio's main research and educational focus.



such as segregation and agglomeration of the minor components, which can adversely affect homogeneity, are examined. Techniques to measure both homogeneity and segregation tendencies are discussed. The density and the flowability of raw materials, drug preblends, and lubricated blends are measured and correlated. The activities are designed for a class of typically 20 students, which allows separating them into groups that will later compare and discuss the effect of using different operating conditions.

In the Materials and Methods section, the techniques needed to measure each of the properties of interest are described. The Results section presents and discusses the measurement obtained by a group of students. A Summary and Conclusion section provides concluding remarks.

MATERIALS AND METHODS

Raw materials

The formulation contains the following components: 84% Fast Flo lactose (Foremost Farms), 15% acetaminophen (APAP, Mallinckrodt) and 1% magnesium stearate (Mallinckrodt). The mass of each component to be added to the blender is given by the different terms on the right side of Eq. (1).

$$\text{Volume} = \frac{W}{\rho_{\text{Ace}}} .15 + \frac{W}{\rho_{\text{Lac}}} .84 + \frac{W}{\rho_{\text{Mg}}} .01 \quad (1)$$

where ρ_{Ace} , ρ_{Lac} , and ρ_{Mg} are the bulk densities of acetaminophen, lactose, and lubricant respectively, and w is the total mass of all materials. The bulk density of materials is measured following the procedure described in the section "Testing bulk and tapped density."

Activities

The process (Figure 1) entails preblending drug (APAP) and excipient (*i.e.*, lactose) and, in a second mixing step, adding the lubricant (magnesium stearate) to the formulation. Properties are measured for the raw materials, for the drug pre-blend, and for the lubricated blend. Different groups of students (if possible) should use different conditions for the blender, such as fill level (40% of the total volume, 80%, etc.) and initial layout of the minor component in the blender (layered, one side, etc). The details to perform blending and measure each blend parameters are given in subsequent sections.

Blending APAP and lubricant (in a V-blender or other tumbling blender)

The blender is used in two steps, first to prepare a pre-blend of APAP and excipients, and second to mix the lubricant with the pre-blend. Having several groups of students gives the possibility to study the impact of blender parameters.^[5] In the present case, two teams operate the 1 cu. ft V-blender at 40% of its total capacity (*i.e.*, 0.4 cu. ft.), loading the APAP either through a single side or with a layered method

(Figure 2). In the side method, all the lactose is loaded first into the blender, then all the APAP is introduced into one of the shells of the V-blender (Figure 1). In the layered method, half of the lactose is added into the blender, then all the APAP is evenly distributed in a layer, and finally, the rest of the lactose is added on top of the APAP (Figure 2). The other two teams operate the blender at 80% capacity (0.8 cu. ft), using the same two loading methods for the APAP. Once the V-blender is loaded, it is operated at 30 rpm for 10 minutes. After mixing, two groups of five samples each are collected from each shell of the blender using a Globe-Pharma thief (New Brunswick, NJ) or similar. A thief is an instrument to extract samples from a powder bed. Each sample is collected at a different depth of the shell (Figure 3) and transferred to a glass vial to determine chemical composition using a suitable analytical method. Additionally, a 300-gram sample is extracted to perform density, flowability, and segregation measurements.

Next, the magnesium stearate (lubricant) is added into the blender through the valve at the bottom (Figure 1) and mixed for another 10 minutes at 30 RPM. Samples are collected again from both shells with the Globe-Pharma thief and a 200-gram sample of the blend is taken to measure density, flowability, and the segregation of APAP and magnesium stearate. The composition of these samples is determined with a suitable analytical method.

Sampling the blender (Global Pharma thief or other)

Sampling is the most important task for assessing homogeneity. The FDA provides guidance regarding tools and methodologies,^[6] and more importantly, most sampling tools have been characterized.^[7,8] The thief sampler (Global Pharma) is one of several sampling tools available. The thief is inserted into the blend, and the operator opens the sampling cavities using a handle at the other end of the sampler. Powder fills the cavities, which are subsequently closed, trapping the powder samples. The design of the thief allows extracting one to three samples at a time. Samples are 0.5-1.5 grams each, depending on the size of removable dies used.

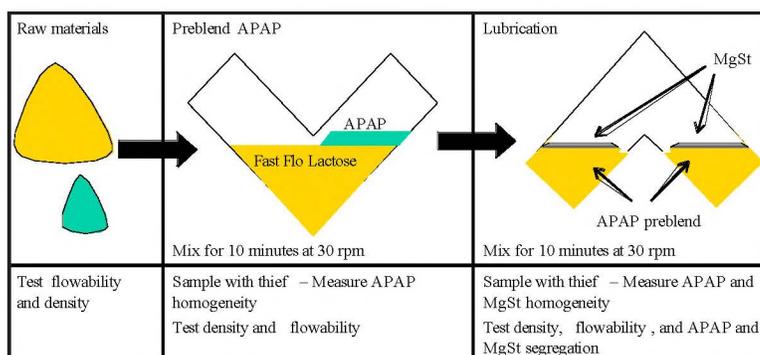


Figure 1. Three stages in the mixing process development.

Determine sample concentration (NIR or other technique) and homogeneity

There are many techniques available to determine APAP and lubricant concentration in samples (e.g., UV, titration, conductimetry, NIR). Although USP recommends a technique for a given component, sometimes there are situations in which it is necessary to consider alternative analytical methods. For an educational activity, the instrumentation available in the lab may determine the selection of the technique. The technique used in the present study is NIR spectroscopy, a non-destructive technique^[9,10] that allows a fast assessment of concentration because it does not require sample dissolution (as in UV or conductimetry) or any other sample preparation (although it assumes that the sample itself is homogeneous). The technique requires developing a calibration equation using standard samples with a known drug concentration. Chemometric software (application of mathematical or statistical methods to chemical data), typically provided by the NIR instrument, facilitates the selection of the most appropriate standards to build the calibration equation based on the spectra collected and on the concentration of each standard.

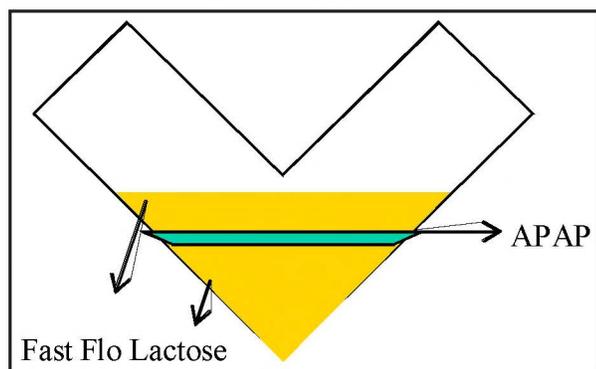
The sample concentrations are used to estimate one of the many indexes available to determine the homogeneity of minor components (APAP and MgSt) in the blend. The index most commonly used in industry is RSD (relative standard deviation).

$$\text{RSD} = \frac{s}{\bar{C}} \quad (2) \quad \text{where } s = \sqrt{\frac{n \sum_{i=1}^n C_i^2 - \left(\sum_{i=1}^n C_i \right)^2}{n(n-1)}} \quad (3)$$

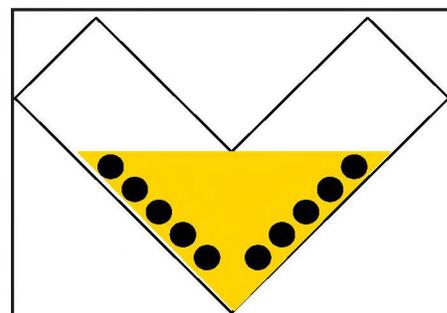
In the previous equations, s is the standard deviation of all sample concentrations, \bar{C} is the average concentration, C_i is the concentration of each individual sample, and n is the total number of samples. The more homogeneous the mixture, the smaller the RSD index. In general, an acceptable value would be below 5% based on samples of ~0.5 grams that are completely assayed by the analytical method.

Measuring segregation (Sifting Segregation Tester)

Segregation of components is one of the main reasons for heterogeneity of pharmaceutical formula-



◀ **Figure 2.** V-blender loaded with the layering method.



▶ **Figure 3.** Sampling positions.

tions. The segregation tester used here (Jenike & Johanson, Tyngsboro, MA) determines sifting segregation, one of the most common types of segregation for pharmaceutical materials.^[11,12] When the flowing layer dilates (a powder usually expands when flowing), smaller particles percolate through a matrix of larger ones. The sifting mechanism is most likely to occur for particles of different size when they flow during filling, transfer, etc.

The tester consists of a steep angle and a shallow angle cone (hoppers), with the steep one initially placed above the shallow one. The upper hopper is filled with the formulation, which is discharged into the lower hopper and then recirculated into the upper hopper. This process is repeated 10 times in order to maximize segregation. Finally, several samples are collected at the discharge of the lower hopper and their concentration determined with NIR.

Testing bulk and tapped density

The bulk and tapped densities are evaluated for the raw materials, for the APAP blend, and for the lubricated blend. The compaction ability of a powder or blend is an important property because it correlates with its ability to flow. Additionally, it can be used to estimate the amount of material that will go into the dies of a tableting machine.

Bulk density is evaluated by filling a 100 ml graduated cylinder with material and determining its net weight. In order to determine the tapped density, the cylinder is "tapped" ~1000 times in a density tester (VanKel, Model 50-1200) and the new volume for the same amount of material is measured. The tester provides a fixed drop of one-half inch at 300 taps/min.

Measuring flowability (prediction and flow tester)

Flowability should be assessed for the raw materials, for the preblend of APAP, and for the lubricated blends. The flowability of powders and blends can be assessed using predictive correlations and direct experimental measurements. Among the predictive correlations, there is the Carr index,^[13] which uses the bulk and tapped density to estimate the flowability of the blend. Flowability is classified according to the value of the Carr compressibility index (C.I. = (tapped density – bulk density)/tapped density * 100) as: Excellent (0-11%), good (12-16%), fair (18-21%), poor (25-35%), and very poor (>33%).

The flowability of blends can be measured using a number of devices (e.g., hoppers, flow testers). In the activities reported here, flowability is measured using a flow tester (PTG-S3 system). This instrument measures the time it takes for 100 grams of material in a funnel to flow through a specified pouring nozzle. When powder flow starts, it is detected by two IR sensors, which activate a timer. As soon as there is no more powder flow, the funnel is closed and the timer stops. A stirrer is sometimes needed in the funnel as some pharmaceutical materials will not start flowing without assistance. The test should be repeated five times, and the deviation of results should not exceed 5%.

The comparison of flow indexes and the direct flow measurements is an interesting exercise that allows students to understand the correlation between ability to densify and flowability.

TYPICAL RESULTS

Bulk and tapped density, and flowability of pure materials and blends

The density measurements are used to estimate the amount of material needed to load the blender, and to estimate the Carr compactability index (an indication of the compressibility of a powder). Bulk and tapped density measurements are performed four times (each group takes one measurement) using the 100 ml graduated cylinder, and the average and standard deviation are calculated. Table 1 shows the average and the standard deviation of the four values. As expected, bulk densities are always lower than tapped densities, and lubricated blends are more dense than the premix. In general, there is more uncertainty (larger standard deviation) in the measurement of bulk density because it is more sensitive to the manner of loading the graduated cylinder (i.e., effect of the operator). In the case of lubricated blends, the different conditions of operation (i.e., fill level and loading of minor components) of the blender introduce an additional source of variation for the measurement.

The flowability of raw material and blends is predicted with the Carr index and measured using the Flow tester PTG-S3 (Table 2). Preblends of APAP do not flow through the tester. Lubricant

addition improves the flowability in all cases.

Homogeneity and segregation of minor components

Table 3 shows the APAP concentration of samples extracted

from the right and left shell (R or L) of the V-blender in the APAP preblend step and in the lubrication step. In the same table, the average concentration, the standard deviation of concentration [Eq. (3)] and the homogeneity index [Eq. (2)] are estimated for each shell of the blender and for the entire blender for

TABLE 1
Bulk density (B.D.) and tapped density (T.D.) for different materials (gr/ml) and the standard deviation of the measurements (of 4 readings).

Raw materials	APAP preblend	Lubricated Blend
Lactose. B.D.: 0.613 (2.26 %), T.D.: 0.695 (3.62 %) APAP. B.D.: 0.355 (3.75 %), T.D.: 0.588 (1.67 %)	B.D.: 0.529 (3.89 %), T.D.: 0.690 (1.19 %)	B.D.: 0.645 (2.02 %), T.D.: 0.798 (1.23 %)

TABLE 2
Flowability Indexes (C.I.) and Measurements (PTG-S3)

Raw materials	APAP preblend	Lubricated blend
Lactose. C.I.: 11.8; PTG-S3: 5, 5.3, 5.7, 5.7 sec. APAP. C.I.: 39.67; PTG-S3: no flow	C.I.: 23.24; PTG-S3: no flow	C.I.: 19.20; PTG-S3: 8.9, 12.1, 11.1, 10.3 sec.

TABLE 3
APAP Concentration Values for the Right (R) and Left (L) Legs of the Blender

conditions	APAP in preblend				APAP in lubricated blend			
	series 1		series 2		series 3		series 4	
	80%, top-bot	40%, top-bot	80%, side-side	40%, side-side	80%, top-bot	40%, top-bot	80%, side-side	40%, side-side
R1	13.61	12.94	12.30	10.31	14.88	14.62	14.39	15.62
R2	13.53	13.61	12.55	10.12	14.54	14.81	14.09	14.47
R3	13.02	14.77	21.85	11.34	14.87	14.92	14.76	15.05
R4	13.62	13.47	12.81	11.93	15.69	14.76	15.81	15.20
R5	13.27	13.93	12.94	13.06	15.64	14.64	17.61	14.96
R - Average	13.41	13.74	14.49	11.35	15.12	14.75	15.33	15.06
R - SD	0.26	0.68	4.12	1.21	0.51	0.12	1.43	0.42
R - RSD %	1.92	4.92	28.46	10.63	3.40	0.84	9.32	2.77
L1	13.16	13.07	12.50	12.64	15.46	15.11	15.53	17.44
L2	12.77	14.51	12.81	12.95	14.73	14.87	14.78	14.90
L3	19.90	13.01	12.32	12.95	15.28	14.91	14.32	15.47
L4	13.83	15.56	13.46	12.68	15.47	15.36	15.82	14.49
L5	13.64	12.76	12.87	14.77	16.05	14.88	16.04	17.14
L - Average	14.7	13.8	12.8	13.2	15.40	15.02	15.30	15.89
L - SD	3.0	1.2	0.4	0.9	0.47	0.21	0.72	1.33
L - RSD %	20.2	8.8	3.4	6.7	3.07	1.39	4.74	8.37
Total Average	14.0	13.8	13.6	12.3	15.26	14.89	15.32	15.47
SD	2.1	0.9	2.9	1.4	0.49	0.22	1.07	1.03
RSD %	14.9	6.7	21.3	11.4	3.20	1.46	6.98	6.63

different APAP loading conditions and fill levels. In Figure 4, the global RSD values for APAP are plotted as a function of fill level of the blender. Four series of data can be identified in this figure; the first two correspond to the RSD for APAP in the preblend (one series for each APAP loading method) and the last two correspond to the RSD for APAP, after lubricating the preblends. The top-bottom loading method for APAP always leads to more homogeneous blends (smaller RSD values) than the side-side loading method (series 1 has larger values than series 2 and series 3 has larger values than series 4). Lubrication enhances APAP homogeneity (series 3 has smaller RSD values than series 1 and series 4 has smaller values than series 2). A larger fill level always leads to a less homogeneous mixture (*i.e.*, larger RSD value), and this variable has a larger impact at short mixing times (series 1 and 2) than at longer mixing times (series 3 and 4). These variables do not have an effect on the homogeneity of the different shells.

The APAP and lubricant segregation tendencies are determined using portions of the lubricated blend. The blend portions are processed with the segregation tester, and the segregation index is estimated using a group of samples collected at the outlet of this tester. Table 4 compares the RSD of the initial blend and the RSD of the samples from the segregation tester for APAP and for the lubricant. The RSD of APAP in the blender is larger than the RSD index of the segregation samples. Not only does the blend not segregate, but, in fact, more mixing occurs as we pass the blend through the funnels of the segregation tester, yielding more homogeneous samples. Therefore the RSD in the blender is not affected by APAP segregation, and instead reflects the effects of fill level and loading method.

Conversely, the RSD index for magnesium stearate in the blender is, in general, smaller than for the segregation samples (Table 4). This indicates that the homogeneity of magnesium stearate becomes worse in the tester as a result of segregation.

Summary: Main observations

The activities show that the APAP homogeneity is affected by the loading method of APAP, the fill level of the blender, and the lubrication of the blend. The segregation test shows that while the APAP does not segregate, the lubricant does. Lubrication leads to the densification and the improved flowability of the blends. In order to carry out the homogeneity test in a reasonable time frame, the sampling of the blend is not extensive (~10 samples). Although this does not confer a strong statistical significance to the homogeneity results, the results obtained by different groups are coherent and show trends and effects of different variables (*e.g.*, fill level and method of loading for homogeneity).

CONCLUSIONS

The main objective of this paper is to present an activity illustrating several aspects of pharmaceutical powder process development. The procedure to evaluate blend properties (homogeneity, segregation, density, and flowability) is described and the analysis of results takes inter-relations among properties of the blend (*e.g.*, between segregation and homogeneity, between flowability and density) into consideration. If several groups of students are available, then there is the possibility to study the effect of operating parameters of the blender (*e.g.*, fill level, loading method of minor components) on blend properties.

REFERENCES

1. Tordesillas, A., and D. Arber, "Capturing the S in segregation: A simple model of flowing granular mixtures in rotating drums," *International J. of Mathematical Education in Science and Technology*, **36**, 861 (2005)
2. Fritz, M.D., "A Demonstration of Sample Segregation," *J. of Chemical Education*, **82**, 255 (2005)
3. Pisano, G.P., "Knowledge, Integration, and the Locus of Learning: An Empirical Analysis of Process Development," *Strategic Management Journal*, p. 85. (1994)
4. "Guidance for Industry. PAT — A Framework for Innovative Pharmaceutical Manufacturing and Quality Assurance," <<http://www.fda.gov/Cder/guidance/6419fnl.htm>>
5. Brone, D., A. Alexander, and F.J. Muzzio, "Quantitative Characterization of Mixing of Dry Powders in V-blenders," *AIChE Journal*, **44**(2), 271 (1998)
6. "The use of stratified sampling of blend and dosage units to demonstrate adequacy of mix for powder blends," *PDA J. Pharm. Sci. Technol.*, **57**, p. 64 (2003)

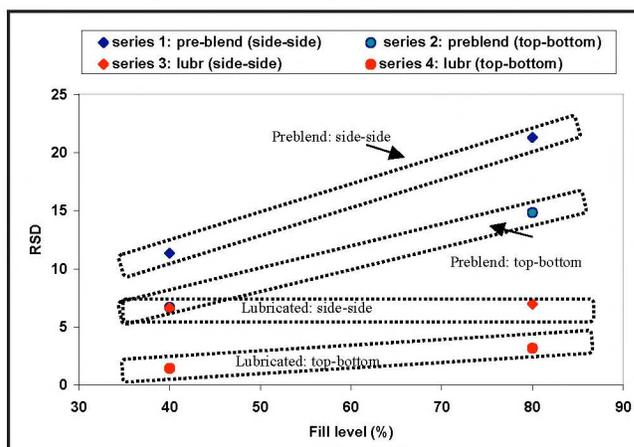


Figure 4. Effect of fill level, loading method and lubrication on the APAP RSD.

	APAP				Lubricant				
	capacity (%)	80	40	80	40	80	40	80	40
loading method	top-bot	top-bot	side/side	side/side	top-bot	top-bot	side/side	side/side	side/side
Blender	14.86	6.70	21.30	11.36	4.03	6.57	10.01	4.35	
Segregation test	3.61	7.46	5.33	3.54	9.02	17.49	9.19	9.06	

7. Muzzio, F.J., *et al.*, "Sampling Practices in Powder Blending," *Int. J. Pharm.*, **155**, 153-178 (1997)
8. Muzzio, F.J., C.L. Goodridge, A. Alexander, P. Arratia, H. Yang, O. Sudah, and G. Mergen, "Sampling and Characterization of Pharmaceutical Powders and Granular Blends," *Int. J. Pharm.*, **250**, p. 51 (2003)
9. Duong, N.H., P. Arratia, F. Muzzio, A. Lange, J. Timmermans, and S. Reynolds, "A Homogeneity Study Using NIR Spectroscopy: Tracking Magnesium Stearate in Bohle Bin- Blender," *Drug Development and Industrial Pharmacy*, p. 679 (2000)
10. Li, W., and G.D. Worosila, "Quantitation of active pharmaceutical ingredients and excipients in powder blends using designed multivariate calibration models by near-infrared spectroscopy," *Int. J. Pharm.*, **295**, p. 213 (2005)
11. Alexander, A., M. Roddy, D. Brone, J. Michaels, and F. Muzzio, "A Method to Quantitatively Describe Powder Segregation During Discharge from Vessels," *Pharm. Tech. Yearbook*, p.6 (2000)
12. Feise, H.J., and J.W. Carson, "Review. The Evolution of Bulk Solids Technology Since 1982," *Chem. Eng. & Tech*, **26**(2), 121 (2003)
13. Carr, R.L., "Evaluating flow properties of solids," *Chem Eng.*, **72**, 163 (1965) □

The Hydrodynamic Stability of a Fluid-Particle Flow: INSTABILITIES IN GAS-FLUIDIZED BEDS

XUE LIU, MAUREEN A. HOWLEY, JAYATI JOHRI, AND BENJAMIN J. GLASSER
Rutgers University • Piscataway NJ 08854

The last few lectures of an undergraduate class in fluid mechanics offer instructors an opportunity to teach students some advanced topics that go beyond the traditional course material.^[1] Fluid-particle flows, where both the fluid and particle are in motion, are prevalent in many industries including the chemical, materials, and energy industries.^[2] In the pharmaceutical and biotechnology industries, which are hiring unprecedented numbers of chemical engineers, nearly all manufacturing facilities involve multiple processing steps that include fluid-particle flows. In spite of the industrial importance of fluid-particle flows, they are rarely covered in any depth in a fluid mechanics course.^[3] Moreover, it is difficult to find examples of fluid-particle flows where undergraduates have the necessary background to handle the equations and analysis that is necessary if more than a survey of the material is to be achieved.

The hydrodynamic stability of a fluid in motion is a fundamental concept in fluid mechanics.^[4] In an undergraduate fluid mechanics class, students are usually introduced to hydrodynamic stability during discussions of the transition from laminar to turbulent pipe flows,^[5] but a detailed understanding of hydrodynamic stability is not critical for most single-phase flow examples. In multiphase flows, however, flow instabilities, density waves, and nonuniform flows are generic. Thus controlling and understanding flow instabilities is crucial for numerous industries that process fluid and particles.

Here we present a fluid-particle example, a gas-fluidized bed, that has been taught at Rutgers in the fluid mechanics class. It relies on a student's knowledge of the Navier Stokes

equations together with Taylor series and complex numbers to perform a fluid-particle stability analysis. At Rutgers, students have already learned Taylor series and complex numbers in a previous math class by the time they take the fluid mechanics class in their junior year. The fluid-particle flow problem presented for analysis has been simplified as a single-phase compressible fluid acted upon by a force representing the fluid-particle drag force, and analytical solutions can be obtained for this simplified system. Thus the model looks like the Navier Stokes equations with an extra term. The problem could be easily implemented in a Fluid Dynamics or Transport Phenomena course in the chemical or mechanical engineering curriculum or an Applied Math course in Fluid Dynamics. In general, we would like to provide students with a fundamental understanding of fluid-particle flows and linear stability theory.

Xue Liu received his B.S. and M.S. from Tsinghua University, and his Ph.D. from Rutgers University. He is currently a research associate of Chemical and Biochemical Engineering at Rutgers University.

Benjamin J. Glasser is an associate professor of Chemical and Biochemical Engineering at Rutgers University. He earned degrees in chemical engineering from the University of the Witwatersrand (B.S., M.S.) and Princeton University (Ph.D.). His research interests include gas particle flows, granular flows, multiphase reactors, and nonlinear dynamics of transport processes.

Maureen A. Howley received her B.S. from the University of New Hampshire and her Ph.D. from Rutgers University. She is currently a physics teacher at Mounts Saint Mary Academy in Watchung, NJ.

Jayati Johri received her B.S. from the University of Texas at Austin, and her Ph.D. from Rutgers University. She is currently a design engineer at GE Water and Process Technologies.

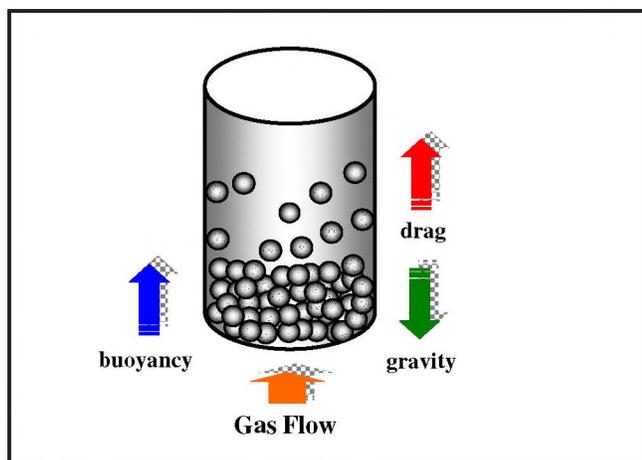


Figure 1. Fluidized bed.

In fluid mechanics, stable flow is best described as flow that will be maintained in spite of small disturbances or perturbations to the flow. The flow is unstable if a small disturbance will lead to the flow to progressively depart from the initial base state.^[6] The study of hydrodynamic stability thus involves determining when the state of fluid flow becomes unstable to small perturbations, and how instabilities evolve in space and time.^[4, 7]

In stability theory, flow behavior is first investigated by performing a linear stability analysis of steady state solutions satisfying appropriate equations of motion and boundary conditions. The stability of such a system is determined by examining its reaction to all possible infinitesimal disturbances to basic steady flow. These results provide the groundwork for further investigation of development of instabilities and evolution of unstable waveforms. Since these methods of analysis involve the linearization and numerical integration of nonlinear partial differential equations of motion, this can lead to many technical difficulties in all but the simplest of flow configurations, and thus is difficult for undergraduate students. To avoid these difficulties, the following problem demonstrates how the stability of a two-phase flow system can be examined using a single-phase compressible flow model, which has been shown to capture the salient features of instability development in the physical system it represents.

PHYSICAL PROBLEM

The gas-fluidized bed consists of a vertical column containing particles supported by a porous bottom (distributor) plate (Figure 1). When a gas is introduced to the column through the distributor, the particles remain stationary until the drag force exerted by the upward flow of gas is balanced by the weight of the bed. At this point, the particles become mobilized, and the bed transitions from being packed to fluidized. In some cases, the bed can expand uniformly at points beyond the minimum fluid velocity u_{mf} with relatively little particle motion (see Figure 2a depicting uniform or *particulate* fluidization).

For most cases, however, uniform fluidization is restricted to a narrow fluidization velocity range bounded by u_{mf} and the commencement of bubbling, u_{mb} . At this point, the bed becomes hydrodynamically unstable to small perturbations and lends itself to the formation of vertically traveling voidage waves that can become spatially amplified in the bed and bring about complex and turbulent flow behavior (see Figure 2b depicting bubbling or *aggregative* fluidization).

In the fluidization research, instability behavior in gas-fluidized beds has been examined by hydrodynamic stability analysis since the early 1960s. Flow instabilities in these systems are in the form of “traveling waves.” The physical manifestation of the traveling wave solution in a fluidized bed takes the form of particle free voidage waves (*e.g.*, bubbles, slugs, and other waveforms), as well as dense particle-cluster formations, which can move violently throughout the bed and dramatically impact process performance and safety^[2] (see Figure 2b). Since fluidized beds are of tremendous importance in industry, the onset and behavior of the unstable flow regime must be well characterized by analysis of the equations governing fluid and particle flow.

Continuum arguments have been used to develop equations of continuity and motion for describing the behavior of the fluid and particle phases in a similar way to the development of the Navier-Stokes equations for Newtonian single phase flows.^[8] The multiphase continuum approach has been used quite successfully for predicting the onset and propagation behavior of instabilities in gas-fluidized beds. Recently, it has been shown that the salient features of instability development in gas-fluidized beds predicted using the multiphase continuum approach are also captured using a single-phase flow model for a compressible fluid acted upon by a density dependent force provided by the drag force.^[9, 10] This simplified model takes a form similar to the Navier Stokes equations for fluid flow. While this problem is quite significant in itself for gaining physical insight into the development of density waves in fluidized beds, it also presents an opportunity for chemical engineering students to develop analytical skills for examining the hydrodynamic stability of a fluid-particle flow using a simple flow model.

MODEL EQUATIONS

The underlying assumption of the Johri & Glasser^[9, 10] model is that a nonuniform suspension of particles fluidized by a gas can sometimes behave (in the continuum) like a Newtonian compressible “fluid” whose motion can be related to the solids in a fluidized bed. From this point on the term “fluid” will be used in this context where “gas” refers to the fluidization medium. Based on the assumption that the inertial and viscous force terms in the gas phase equation are negligible, these authors simplified the multiphase model to equations of continuity and motion for a single fluid having variable density. Continuum equations of continuity and motion for

the fluid are respectively written as^[10]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \underline{v}) = 0 \quad (1)$$

$$\rho \left(\frac{\partial \underline{v}}{\partial t} + \underline{v} \cdot \nabla \underline{v} \right) = \underline{F} - \nabla \cdot \underline{\underline{\sigma}} + \rho \underline{g} \quad (2)$$

where the density of the Newtonian fluid (ρ) varies linearly with the solids volume fraction ϕ as $\rho = \rho_s \phi$, and ρ_s is the absolute particle density. The fluid velocity vector is represented by \underline{v} ; $\underline{\underline{\sigma}}$ is the fluid phase stress tensor; and \underline{g} is the gravity force vector. The density dependent force \underline{F} represents the drag force exerted on the particle assembly by the gas flow. Eqs. (1) and (2) represent equations of continuity and motion for a compressible fluid and are exactly what students would be exposed to in a course in fluid mechanics except for the additional density dependent force, \underline{F} .

Continuum arguments provide constitutive relations for the various terms. Johri & Glasser^[10] adopted a suitable closure for $\underline{\underline{\sigma}}$ motivated by the work of Anderson & Jackson,^[11] which takes a form analogous to that for a Newtonian fluid:

$$\underline{\underline{\sigma}} = P \underline{\underline{I}} - \mu \left[\nabla \underline{v} + (\nabla \underline{v})^T - \frac{2}{3} (\nabla \cdot \underline{v}) \underline{\underline{I}} \right] \quad (3)$$

where μ is the viscosity of the fluid (assumed to be constant

in this analysis), and P is the pressure, which is dependent on particle volume fraction ϕ , or, in this case, ρ . This pressure term is analogous to the pressure of an ideal gas, which is a function of gas density. We will examine flow only in the vertical dimension (x), in which case there is no variation in the other two directions (y and z) thus equations 1 and 2 are written as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \quad (4)$$

$$\rho \left(\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} \right) = - \frac{\partial P}{\partial x} + F + \mu \left(\frac{4}{3} \frac{\partial^2 v}{\partial x^2} - \rho g \right) \quad (5)$$

where $v = v_x$ and $F = F_x$. Linear forms for F and P are adopted and these represent the simplest possible forms capable of capturing the hydrodynamic instability:

$$F = A\rho + B; \quad P = E\rho \quad (6)$$

where A , B , and E are appropriately assigned constants consistent with experimental evidence of gas-fluidized bed behavior.

LINEAR STABILITY ANALYSIS PROCEDURE

As stated in the Introduction, hydrodynamic stability of a system is first investigated by linear stability analysis (LSA)

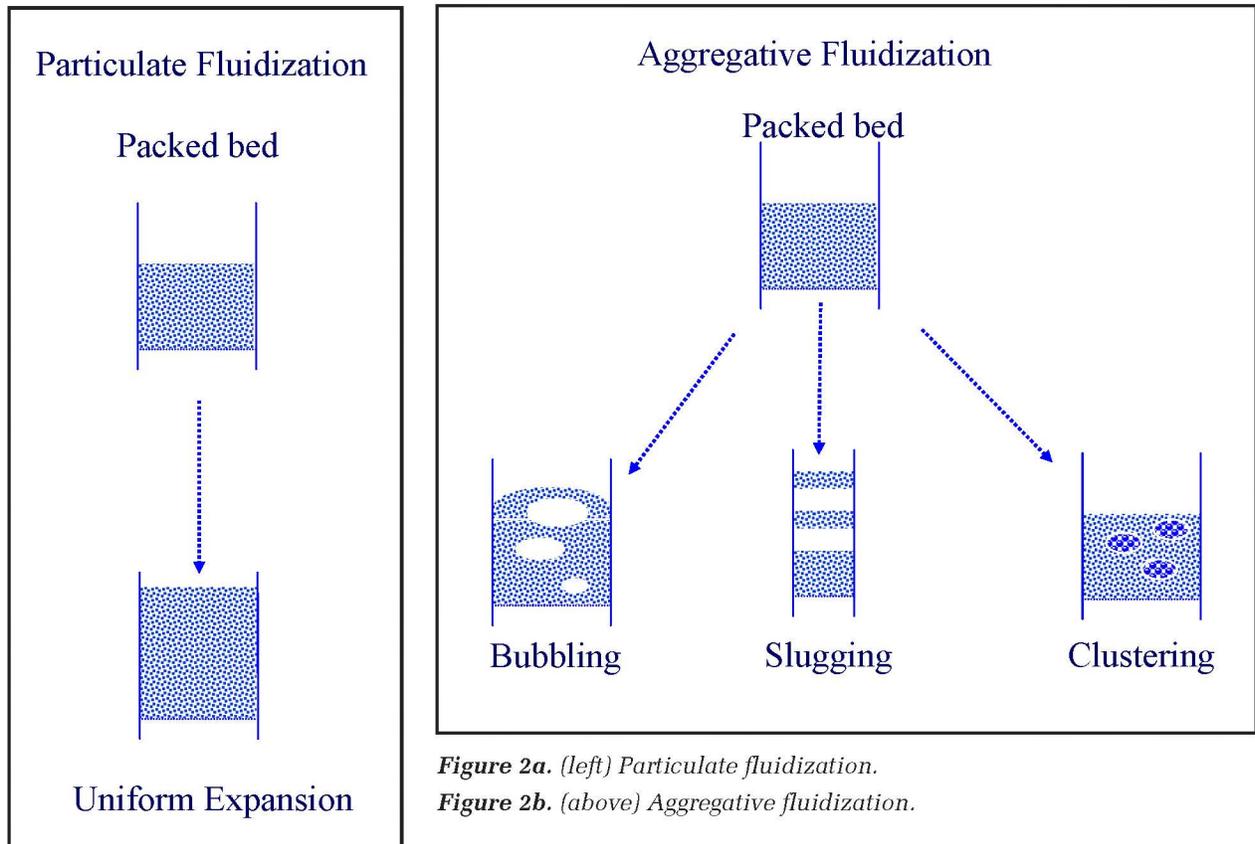


Figure 2a. (left) Particulate fluidization.

Figure 2b. (above) Aggregative fluidization.

of steady state solutions satisfying the governing equations. We therefore begin with a linear stability analysis of the steady state solution. Students should perform each of the following steps (in their entirety) either individually or in small groups of two to three students. Discussion is strongly encouraged during the analysis to provide the students with insight into the system's physical behavior. Topics for discussion are provided within the text.

Steady State Solution: Prove that the simplest solution to the set of coupled nonlinear partial differential Eqs. (4) and (5) represents a spatially uniform state of static "fluid" where the density dependent force F is balanced by the gravitational force of the fluid. In particular, show that under these conditions $v_0=0$, $\rho=\rho_0$ and $F_0=\rho_0g$, where $\rho_0=\rho_s\phi_0$ and the subscript '0' is used to designate conditions at steady state. Find numerical solutions for the steady state values of ϕ_0 and F_0 in dilute beds having $\rho_0=220$ and 440 kg/m³ and dense beds with $\rho_0=1100$, 1210 , and 1320 kg/m³ when $\rho_s=2200$ kg/m³. Find the constant B which is chosen in accordance with $F_0=\rho_0g$ for each of these bed conditions and write functional forms for the linear closure for F using parameter values from Table 1.

Linearization: Impose perturbations ρ' and v' on the steady state solution representing infinitesimal changes in density and velocity:

$$\rho = \rho_0 + \rho' \quad v = v_0 + v'$$

Rewrite Eqs. (4) and (5) in terms of the perturbation variables, and perform a Taylor series expansion about the steady state solution. Since the perturbations are assumed to be both small and smoothly varying in space and time, their derivatives are also small. By neglecting terms in the series involving powers of perturbation variables greater than one, and eliminating products of perturbation variables, the students should obtain the following linearized equations in perturbation variables ρ' and v' :

$$\frac{\partial \rho'}{\partial t} + \rho_0 \frac{\partial v'}{\partial x} = 0 \quad (7)$$

$$\rho_0 \frac{\partial v'}{\partial t} = -P'_0 \frac{\partial \rho'}{\partial x} + [F'_0 - g] \rho' + \mu \left(\frac{4}{3} \right) \frac{\partial^2 v'}{\partial x^2} = 0 \quad (8)$$

where:

$$F'_0 = \left(\frac{dF}{d\rho} \right)_{\rho=\rho_0} \quad P'_0 = \left(\frac{dP}{d\rho} \right)_{\rho=\rho_0} \quad (9)$$

We seek a solution to Eqs. (7) and (8) in the form of plane waves since in real fluidized beds the development of the density waves can be observed in the bed:

$$\rho' = \hat{\rho} \exp(st) \exp(i\kappa x) \quad v' = \hat{v} \exp(st) \exp(i\kappa x) \quad (10)$$

where $\hat{\rho}$ and \hat{v} are (complex) amplitudes of the pertur-

bations in density and velocity respectively, and κ is the wavenumber of the disturbance (in one dimension x), having real components, whose wavelength $\lambda = 2\pi / |\kappa|$. In general, s is complex, $s = \sigma \pm \omega i$, where the imaginary part is used to determine wavespeed (c) according to the relationship $c = \omega / \kappa$, and the real part determines the growth or decay rate of the wave with time. If σ is positive, the perturbations grow in time and the base state is unstable, and if σ is negative, the perturbations decay and the base state is stable [see Eq. (10)]. That is, for a positive σ the base state solution will not be observed in practice.

Computational Analysis: By combining Eqs. (7) and (8), we can reduce the linearized PDE's to a single algebraic equation in s by performing the following steps: take the $\partial / \partial x$ of Eq. (8); substitute into the resulting equation using the expression for $\partial v' / \partial x \partial t$, $\partial^3 v' / \partial x^3$ obtained from continuity Eq. (7) and its derivatives to eliminate v' . The student should obtain a single differential equation in the density perturbation variable ρ' :

$$-\frac{\partial^2 \rho'}{\partial t^2} = -P'_0 \frac{\partial^2 \rho'}{\partial x^2} + [F'_0 - g] \frac{\partial \rho'}{\partial x} - \left(\frac{4\mu}{3\rho_0} \right) \frac{\partial^3 \rho'}{\partial t \partial x^2} = 0 \quad (11)$$

A solution for ρ' in the form of Eq. (10) and its derivative forms are then introduced into Eq. (11) to obtain a quadratic expression in s whose roots are given by

$$s = \frac{2\mu\kappa^2}{3\rho_0} \left[-1 \pm \sqrt{1 - \frac{9\rho_0^2 P'_0}{4\mu^2 \kappa^2} - \frac{9\rho_0^2 (F'_0 - g) i}{4\mu^2 \kappa^3}} \right] \quad (12)$$

The resulting growth rate s is thus a function of parameter values ρ_0 , μ , F'_0 , and P'_0 and the wavenumber of the disturbance κ . Moreover, s is complex indicating disturbances propagate through the bed in the form of traveling waves. From Eq. 12, it is clear that we have analytically solved the problem, and numerical analysis used in most multiphase flow simulations is avoided. This will greatly reduce the mathematical difficulty and help students to focus on the stability theory and the problem itself instead of the numerical analysis. Note that a sign error was made in Eq. (23) of Johri & Glasser^[10] and Eq. (18) of Johri & Glasser^[9] where the last term under the square root should be $-$ not $+$. This error resulted in negative computed wavespeeds. Johri & Glasser^[10] discusses the implications of wavespeed direction with respect to fluid flow in order to physically justify their findings. Correct signage, however, [as shown in Eq. (12) of this manuscript] results in computed wavespeeds of equal magnitude to Johri & Glasser results, but in the direction of fluid flow and physically realizable.

RESULTS

Since we are interested in distinguishing waves that become amplified in the bed from those that are damped out, the student should proceed to plot the real part of the growth rate σ versus

wavenumber κ using parameter values from Table 1. These values were chosen to represent glass beads a few hundred micron in diameter fluidized by air. Here, closures for F and P from Eq. (6) are used where $F'_0=A$ and $P'_0=E$. To examine the density effect, the students should compare the linear stability of steady state solutions having low fluid densities, $\rho_0=220$ and 440 kg/m^3 (representing dilute fluidized beds) with steady states having high fluid densities, $\rho_0=1100, 1210,$ and 1320 kg/m^3 (representing particle dense fluidized beds). Results for a high density fluidized bed ($\rho_0=1100 \text{ kg/m}^3$) are shown in Figure 3 where the real part of the growth rate σ is plotted as a function of wavenumber κ . Students should independently generate linear stability curves for each ρ_0 value condition using Mathematica, MatLab or equivalent.

As shown in Figure 3, the curve has positive growth rate σ for a range of wavenumbers beginning at $\kappa=0$. The growth rate then goes through a maximum at σ_m , and then decreases to zero at a critical wavenumber κ_c . Physically, this represents the boundary between disturbances, which become amplified as they propagate through the bed from those that are damped out. Note that the use of linear closures results in the system becoming *more unstable* as fluid density is *increased*, that is, the critical wavenumber κ_c and maximum growth rate σ_m both increase with an increase in ρ_0 . This is because the inertial terms, which drive the instability, increase with an increase in density.

Points for discussion: What do the density dependent force terms physically represent? Use Figure 1 to illustrate that as particles move closer together in the bed to form a more densely packed region, the interstitial gas velocity increases between particles resulting in an increase in particle “drag.” How significant is the effect of closure in the dilute and dense flow regimes? How might the magnitude and direction of this force term serve to damp out or amplify unstable voidage waves? Discuss the physical significance of competing density effects with respect to stability. Why would an increase in the pressure gradient (as opposed to pressure) serve to stabilize the bed? How might one conceive of the origin and growth of low density cluster-like insta-

ρ_0	1100 kg/m^3
μ	0.665 kg/(m.s)
A	14.7 m/s^2
E	0.03 J/kg
c_b	0.173 m/s

In spite of the industrial importance of fluid-particle flows, they are rarely covered in any depth in a fluid mechanics course.

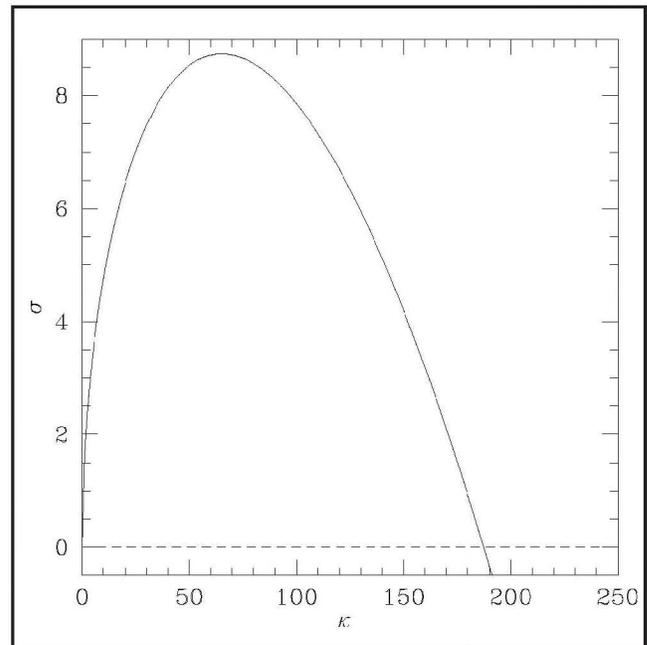


Figure 3. The real part of the growth rate σ (with units of $1/s$) versus the vertical wavenumber κ (with units of $1/m$), computed by a linear stability analysis about the uniform state using linear closures for F and P evaluated at $\rho_0 = 1100 \text{ kg/m}^3$.

	Strongly Disagree		Neutral		Strongly Agree
Category	1	2	3	4	5
Q1			14	11	3
Q2			8	13	7
Q3		3	9	10	6
Q4	1		10	8	9

bilities versus that of bubble-like high density instabilities, and how is this analogous to the behavior of a compressible fluid? What would be the physical manifestation of unstable waveforms in low density and high density flow of a compressible fluid? What is the role of the density dependent force, and what effect does its closure form have? The reader is referred to Johri and Glasser^{9,10} for further discussion of the physical situation.

EVALUATION

The stability theory discussed in this paper has been taught in a chemical engineering course: Transport Phenomena I, at Rutgers University in 2005 and 2006. To spur students' interest in the stability theory, we played experimental videos in the beginning of the class to show the development of the density waves, such as bubbles and slugs in fluidized beds. Such videos are available on a CD from Rhodes.¹² Student feedback in 2006 was obtained by issuing a questionnaire (see Table 2, previous page), in which students had to state to what extent they agreed with four statements on a scale ranging from 1, "strongly disagree," to 5, "strongly agree." Generally, we obtained positive feedback from students. A fair number of students felt that they learned a lot from this lecture (Q1 and Q2 in Table 3), and would recommend teaching this material to the class next year (Q4 in Table 3). Some of the comments from students included "I really enjoyed this class. It really sparked my interest in chemical engineering," "I think the explanations were valuable and showed a great deal of importance," and "It was good because it connected several courses. It is always good to see applications that span different classes." Most students believed that they had adequate math background to understand the mathematical concepts put across in the lecture (Q3 in Table 3). Several students, however, also pointed out that one lecture is not enough to fully understand the stability theory material. Such comments included "Maybe there was less time for all that material," and "It is a good beginning to understanding the material that will grow more in depth." We will focus on this point in future classes.

CONCLUSION

We have presented a simple example of an industrially relevant fluid-particle flow problem, which introduces students to methods of linear stability analysis involving nonlinear partial differential equations. This example demonstrates how the stability of a two-phase flow system can be examined using a simplified single-phase compressible flow model, which has been shown to capture the salient features of instability behavior. Students are expected to perform each step of the analysis, and points for classroom discussion have been noted to provide physical insight into the mechanistic features associated with unstable flow behavior and the physical manifestation of unstable waveforms.

REFERENCES

1. Conesa, J.A., and I. Martin-Gullon, "Courses in Fluid Mechanics and Chemical Reaction Engineering in Europe," *Chem. Eng. Educ.*, **34**, p. 284 (2000)
2. Fan, L.S., and C. Zhu, *Principles of Gas-Solid Flows*, Cambridge University Press, New York (1998)
3. Fan, L.S., "Particle Dynamics in Fluidization and Fluid-Particle Systems," *Chem. Eng. Educ.*, **34**, p. 40 (2000)
4. Drazin, P.G., and W.H. Reid, *Hydrodynamic Stability*, Cambridge University Press, New York (1981)
5. Churchill, S.W., "A New Approach to Teaching Turbulent Flow," *Chem. Eng. Educ.*, **33**, p. 142 (1999)
6. Campbell, L., and W. Garnett, *The Life of James Clerk Maxwell*, Macmillan, London (1982)
7. Chandrasekhar, S., *Hydrodynamic and Hydromagnetic Stability*, Oxford University Press, Oxford (1961)
8. Jackson, R., *The Dynamics of Fluidized Particles*, Cambridge University Press, New York (2000)
9. Johri, J., and B.J. Glasser, "A Bifurcation Approach to Understanding Instabilities in Gas-Fluidized Beds Using a Single Phase Compressible Flow Model," *Computers & Chem. Eng.*, **28**, p. 2677 (2004)
10. Johri, J., and B.J. Glasser, "Connections Between Density Waves in Fluidized Beds and Compressible Flows," *AIChE Journal*, **48**, p. 1645 (2002)
11. Anderson, T.B., and R. Jackson, "A Fluid Mechanical Description of Fluidized Beds: Stability of the State of Uniform Fluidization," *Industrial and Eng. Chemistry Fundamentals*, **7**, p. 527 (1968)
12. Rhodes, M., et al., *Laboratory Demonstrations in Particle Technology*, CD (1999) □

LAB-ON-A-CHIP DESIGN-BUILD PROJECT WITH A NANOTECHNOLOGY COMPONENT *in a Freshman Engineering Course*

YOSEF ALLAM, DAVID L. TOMASKO, BRUCE TROTT, PHIL SCHLOSSER, YONG YANG,
TIFFANY M. WILSON, AND JOHN MERRILL
The Ohio State University • Columbus, OH 43210

Government initiative, market-driven, and research-driven forces have drawn international attention to the emerging field of nanotechnology. Nanotechnology research spans many disciplines in the sciences and engineering, and encompasses advanced materials, electronics, and sensors, as well as biomedical applications.^[1] Although some institutions offer degrees in this area, while others offer

individual courses, as late as 2004 only Cornell University and The Ohio State University offered a full-fledged freshman engineering course that fulfills undergraduate engineering degree requirements and includes a term-length, hands-on nanotechnology design, fabrication, and application project.

In the last decade or more, researchers have investigated and repeatedly stressed the need to change the manner in which

Yosef S. Allam is a graduate teaching associate in the First-Year Engineering Program at The Ohio State University, in which he develops new curriculum and helps with piloting and revising newly implemented curriculum. He holds B.S. and M.S. degrees in industrial and systems engineering from OSU. He is currently pursuing a Ph.D. in engineering education with research interests in spatial visualization, curriculum development, and fulfilling the needs of an integrated, multi-disciplinary first-year engineering environment through the use of collaborative learning, problem-based learning (including design-build projects), classroom interaction, and multiple representations of concepts.

David L. Tomasko is professor of chemical and biomolecular engineering, deputy director of the Center for Affordable Nanoengineering of Polymeric Biomedical Devices, and director of the Honors Collegium at The Ohio State University. He has research interests in molecular thermodynamics, supercritical fluid solutions, and polymer processing.

Bruce Trott is a lecturer in the First-Year Engineering Program at The Ohio State University. He came to OSU in 2002 after 33 years as an engineer in R&D organizations for high-technology companies such as Bell Labs and Lucent Technologies. His roles included software and hardware developer, system integration specialist, senior project manager, software development manager, and corporate manufacturing planner.

Phil Schlosser teaches courses in the First-Year Engineering Program in the College of Engineering at The Ohio State University. Dr. Schlosser holds more than 20 U.S. and foreign patents for various electronic devices and systems. In addition to his teaching activities, he has been instrumental

in starting several electronics companies and developing and teaching courses in innovation and entrepreneurship at The Ohio State University.

Yong Yang is a postdoctoral fellow in the Department of Biomedical Engineering at Duke University. Prior to moving to Duke, he was a Research Associate in The Nanoscale Science and Engineering Center (NSEC) for Affordable Nanoengineering of Polymer Biomedical Devices (ANPBD) at The Ohio State University. He received a Ph.D. in chemical engineering from The Ohio State University in 2005. His research interests include stem cell technology, polymer micro/nanotechnology, polymer nanocomposites, and supercritical fluids technology.

Tiffany M.S. Wilson is a Ph.D. candidate in the Department of Chemical and Biomolecular Engineering at The Ohio State University. She is currently completing her dissertation work at Sandia National Laboratories in Livermore, California. Her research focuses on structure/property relations and processing effects in semiconducting polymers to enable their improved use in micro and nanosystems and detectors for ionizing radiation.

John A. Merrill is director of the First-Year Engineering Program at The Ohio State University College of Engineering. His responsibilities include operations, faculty recruiting, curriculum management, student retention, and program assessment. He also works with the associate dean for Undergraduate Education & Student Services in the establishment of outcome-based assessment processes for program improvement and accreditation. Dr. Merrill received his Ph.D. in instructional design and technology from The Ohio State University in 1985, and has an extensive background in public education, corporate training, and contract research.

engineering is introduced to pre-engineers.^[2-5] From their research, they have proposed integrated curricula incorporating an introduction to engineering, engineering graphics and communication, technical writing, engineering technology tools, engineering ethics, hands-on or active-learning experiences, cooperative or collaborative learning, and teamwork.

During the past 10 years, The Ohio State University's College of Engineering has established a dual offering of integrated course sequences known as Fundamentals of Engineering (FE) and its parallel, Fundamentals of Engineering for Honors (FEH). The goals of FE courses (ENG 181 and ENG 183) are to provide freshman engineering students with knowledge of engineering fundamentals and engineering graphics; skills in engineering communication and engineering problem solving; experience in team-building; knowledge of and ability to apply the design process; ability to make measurements; knowledge of how things work; and experience in a hands-on laboratory. In the second session of the FE program, ENG 183 provides a quarter-long design, fabrication, and implementation project. Students are expected to tend to such issues as initial research, brainstorming, designing, building, testing, and implementation. They are also expected to exercise project management, project economics, and teamwork as they work. Throughout the project, lab memos are assigned on a regular basis and each team gives an oral presentation at the conclusion of the quarter. The instructional goals of the Fundamentals of Engineering course sequence at The Ohio State University are discussed thoroughly by Merrill.^[6]

Previously implemented ENG 183 design projects include designing and building a conveyor that sorts objects of various dimensions and material properties, and building a model

roller coaster that meets specified design and performance criteria. A Lab-on-a-Chip (LOC) design-build project with a nanotechnology component has been developed as a voluntary alternative to the ENG 183 design project. This alternate design-build project was piloted during Winter and Spring Quarters of 2004, with one section offered in each quarter for a total of 127 students then expanded to 3 sections in 2005 with an enrollment of 190 students. It continues to be offered twice annually with a total of 2 sections of enrollment per academic year.

The premise for the Nanotechnology and Microfabrication LOC pilot course for freshmen engineers complements the findings of other researchers seeking to offer courses in nanotechnology and related areas to post-secondary students.^[7-12] By converting knowledge from local graduate and faculty researchers to a format accessible to freshmen, it is hoped that first-year engineering students will acquire the fundamentals of nanotechnology and develop an interest in this and other areas of research. The purpose of this paper is to share the fruits of this effort and provide a high-level presentation of the curriculum developed and preliminary research findings.

PROJECT

Goals

This new project offering represents a significant effort to expose freshman engineering students to cutting-edge research topics and foster an early interest in academic and professional careers in new fields such as nanotechnology and biomedical devices. The project also demonstrates a safe method of incorporating more chemical- and biological-based

engineering disciplines into a freshman laboratory course as an alternative to the traditional electro-mechanical emphasis. A three-pronged approach was employed in developing the project, involving hands-on lab activities, nanotechnology teaching modules, and on-campus nanotechnology research laboratory tours hosted by faculty and researchers. Through oral presentations and formal written reports, students later make connections and draw analogies between the top-down microfabrication methods used in their project and the nanotechnology and nanofabrication technologies discussed in the teaching modules they read and the nanotechnology research laboratory tours. In doing so, they recognize the challenges associated with engineering at the nanoscale, and hopefully get interested in doing research in this area. The lab activities included a quarter-length

TABLE 1
Lab Topics and Activities

Lab Session	Topics / Activities
1	Introduction: Nanoscale Definitions, Techniques, Devices Hands-on experimentation and benchmarking.
2	Fluid mechanics, capillary flow, clean room practices Advanced capabilities testing. Begin design.
3	Lab Tours or Sensor Circuit Design I Paper chip design, operational design, calculations due.
4	Lab Tours or Sensor Circuit Design I Final CAD design in Inventor, operational design, calculations due.
5	Sensor Circuit Design II Dilution of concentrations and detection device calibration.
6	PDMS Chip Molding, Prototype Chip, Sketch Designs, Manufacturing Principles 2 chips per team.
7	Chip Demolding & Assembly, Production, Economics Initial testing.
8	Chip Fluidics Test, History of IC Talk & Relevance to Micro- & Nanotechnology
9	Final Chip Test Determine unknown concentration based on calibration; competition.

design, build, and test problem using project management and team-building skills found in the standard lab sections.

Premise

Fluorescein is a chemical used to detect an eye disorder known as dry-eye syndrome. Typically, testing for this condition requires expensive instruments in a doctor's office. Samples of tears are taken from the eye in micro-liter amounts. Thus, students are told the project's objective is to design a cheap, portable LOC to measure the concentration of fluorescein. The benefit of this device would be to greatly reduce the cost of equipment required (fluorimeters) as well as to provide a product that is readily portable. Portability is very helpful in situations where older or disabled patients find it difficult to travel to a doctor's office. Thus, the students are given a real-life premise for their project.

Laboratory Activities

The overall design objective given to the students is to design, fabricate, and operate an LOC made from polydimethylsiloxane (PDMS) capable of optically detecting the presence and quantity of an agent via detection of emissions from a fluorescent tracer using an electronic detection device built by the students. The LOC integrates biochemical analysis with proper microfluidic components (such as sample dilution, pumping, mixing, metering, incubation, separation), and detection in micron-sized channels and reservoirs into a miniaturized device. The integration and automation involved can improve the reproducibility of the results and eliminate labor, time, and sample-preparation errors that occur in the intermediate stages of an analytical procedure.

Table 1 summarizes the lab activities. The hands-on activities expose students to the design process in which, after significant benchmarking and analysis, they design, revise, and build a prototype based on the lessons learned earlier in the quarter with a generic design. They also experience firsthand the importance of proper calibration of a detection and measurement device and use their calibration data to derive a curve and function that is employed in testing and determining the concentration of an unknown sample. Because the student teams are exposed to important engineering topics such as analysis, design, synthesis, calibration, and testing with a microfabrication and nanotechnology focus, the hands-on activities represent the most important focus of this project.

Chip Design and Fabrication

The four-member student teams spend the first two weeks benchmarking a generic chip design with experiments to determine performance on various features. In the first four weeks, the student teams design their own chip by using knowledge gained from the benchmarking activities to produce a chip that will outperform the generic design. Chip design, mold fabrication, and molding processes are based on ongoing research^[13-16] in the Department of Chemical and Biomolecular Engineering.

A chip is comprised of wells and channels connecting those wells. Required components include: staging wells for sample and solvent, flow-through detection well, and a waste well to accept solvent wash and unused reagent from the detection well. Figure 1 shows the currently used generic chip design. The student teams are provided with requirements and constraints regarding channel and well sizes. Additionally, capillary action is presented and capillary check valves can be an optional component in the design.

Provided with design constraints and given two lab periods to explore the workings of a prototype device, the students will note nuances of the generic design and its performance and use insight gleaned from this lab to understand design considerations in building a better chip and the importance of proper equipment and procedure. The generic design is not a particularly good design, as some shortcomings have intentionally been incorporated for the students to investigate. After benchmarking, they are encouraged to brainstorm and then narrow ideas based on the constraints, requirements, and information needs of the project. They are encouraged to be creative, while keeping the overall function of the chip in mind. The students must also be mindful that only a single prototype iteration is possible due to time constraints. The students sketch a design of the channels and wells of the chip. They are also required to author an operational design—essentially procedures on the use of the chip—as well as provide design notes including calculations and similar justifications for particular design characteristics. Upon instructional team review, the student team finalizes its design and uses Autodesk Inventor to prepare a true-scale drawing of the microfluidic LOC within a 2" (5.08 cm) circle. Profiles of sample student designs are

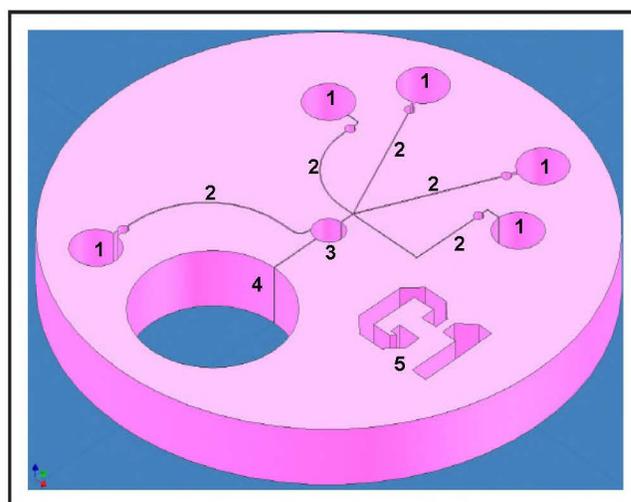


Figure 1. Autodesk Inventor rendering of generic chip design: 1 – Staging wells; 2 – Channels with in-line capillary valves; 3 – Detection well; 4 – Waste well; 5 – Team logo.

provided in Figure 2. Most student designs are improvements over the generic design, as they find ways to avoid the difficulties encountered during their investigations in the first two labs, while providing a more aesthetically pleasing final result.

The files are sent out for printing on transparency at 16000 DPI and the transparency is used as the photomask for photolithographic production of a mold on a silicon wafer. Standard photolithography procedures with SU 8-2075 photoresist (MicroChem Co.) are used for a target feature thickness of 150 microns.^[4] This back-end process is performed by graduate student fellows in our Nanoscale Science and Engineering Center (NSEC). During these background activities, which require a total of 3 weeks (weeks 3-5 of the session), the student teams build their detection circuits, take and report on lab tours of campus nanotechnology research facilities — where some students may have the opportunity to meet the graduate student volunteers performing the back-end processing on their chips — and experiment with their newly built detection devices with the generic chips prepared in advance by the instructional team.

The processed wafers are returned to the student teams in the sixth lab session and the teams produce a polydimethyl siloxane (PDMS) casting from the silicon wafer mold as well as a flat lid. Each of the castings is contained in a polystyrene Petri dish. The PDMS resin (Sylgard 185, Dow Corning) and curing agent represent a very safe crosslinking polymerization that can be carried out with straightforward safety precautions (goggles and gloves). Students are introduced to and required to read the Material Safety Data Sheets (MSDS) for these chemicals prior to use. Details regarding mixing, degassing, and molding are provided in the lab procedures.

In the subsequent lab session (after several days curing at ambient temperature), the PDMS chip is ready to demold. A small spatula is used to separate the PDMS from the sides of the Petri dish and then the student very slowly pulls the PDMS (often with the wafer attached) out of the Petri dish. The wafer is carefully separated from the PDMS and the 2" patterned area is isolated using a 2" punch. Finally, a 2" flat lid is also punched out from the PDMS in the second Petri dish.

Chip-Chip Holder Assembly

A 1:1 (full scale) outline of the chip and chip holder design is printed out from the Inventor file to assist assembly of the chip and chip holder. The PDMS lid is aligned on the top of the outline printout. The center of the staging wells and waste well access ports are marked with a small dot of a permanent marker. A leather punch is used to punch the 1/8" diameter holes centered on the marked spots. These access holes punched in the lid will later have plumbing inserted for sample delivery and flushing. Prior to alignment and assembly, the students clean all the chip assembly components with an ultrasonic cleaner in a detergent solution. The pieces are rinsed with distilled deionized water.

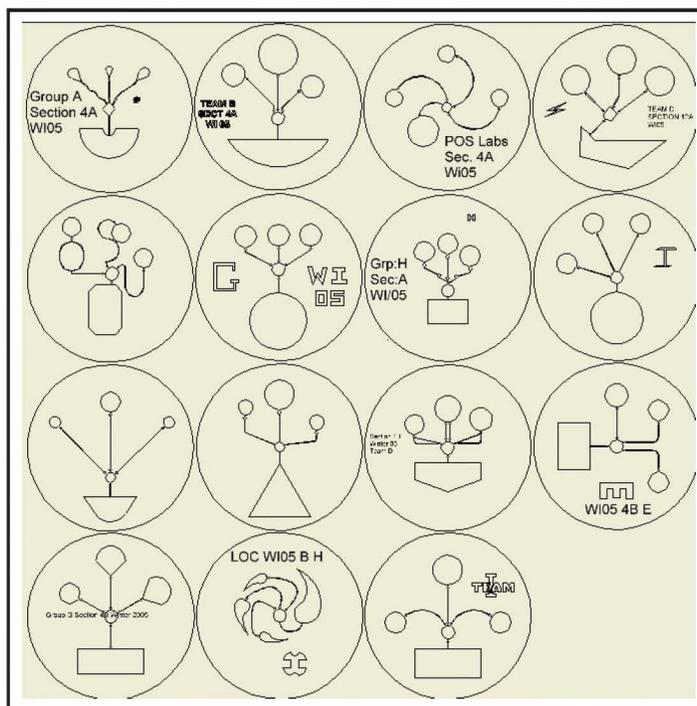


Figure 2. Sample student design profiles.

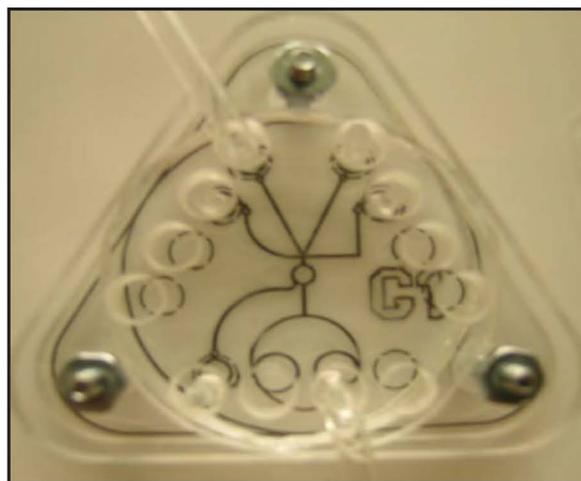


Figure 3. PDMS chip, PDMS lid, and chip holder aligned and assembled over transparency.

The Plexiglas bottom of the chip holder is placed on the outline printout and aligned precisely. The PDMS chip is transferred onto the base, patterned channels facing up and lined up with the design on the outline. The detection well is correctly located and the staging wells are carefully aligned with access holes. The PDMS lid is then aligned to the design on the outline and chip. The Plexiglas chip holder top is then placed over the entire assembly. It is imperative that there are no air bubbles between the parts. Finally, the three nuts are tightened only as much as necessary to hold the top in place and maintain a seal. It is important not to apply too much

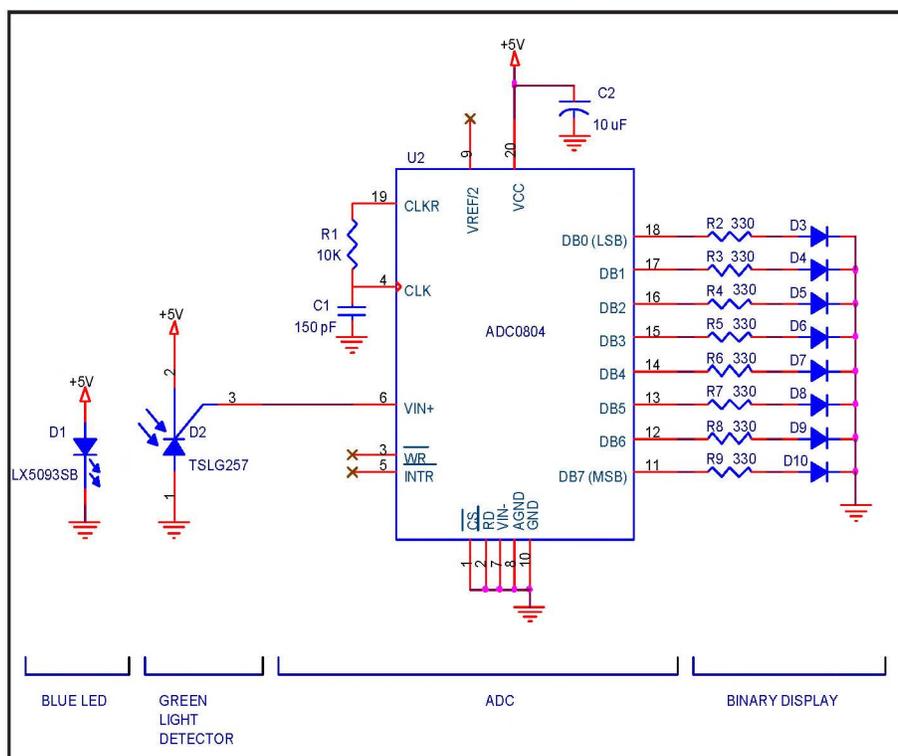


Figure 4. Detection circuit schematic. ADC0804 is an analog-to-digital converter 20-pin IC. Each team constructs this circuit on a prototyping board.

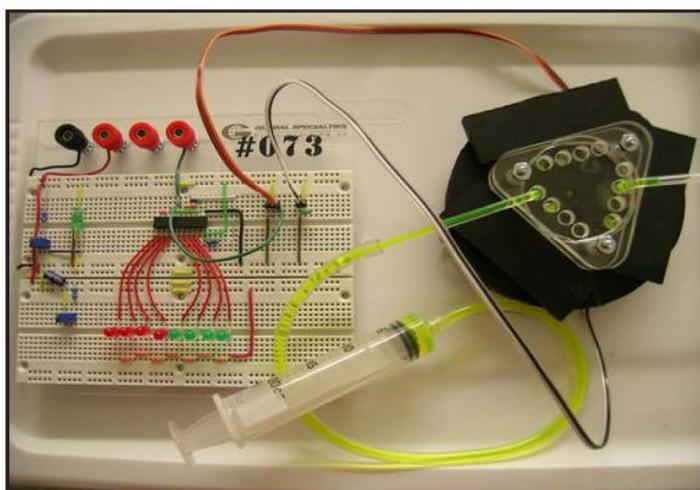


Figure 5. Detection and calibration setup with the generic chip.

torque to the nuts to avoid deformation. The finished chip-chip holder assembly is shown in Figure 3.

Upon assembly, the chip is tested for proper fluid flow. Glass plumbing is inserted into the access holes at the top of the device. Syringes are used to pump dyed water into the detection well. Then clear deionized water is used as a flushing agent in the same fashion it would be used with real samples. It is during this stage that the students are expected to gain valuable experience in manipulating samples in their chips and troubleshooting any sealing, incomplete filling, or other operational issues.

From the remainder of the seventh lab through the open eighth lab, the student teams are expected to refine their operation procedures and prepare for the final test, which is held in the ninth lab.

Detection

During the lab sessions in which the chips are being fabricated, basic electronics are discussed along with photometric detection methods while the students build and calibrate their electronic optical detection devices. The detection device consists of a blue-light LED excitation source and green-light photosensor for detecting emitted photons integrated with an analog-to-digital converter. An electric circuit, which is built on a prototyping board (PB) and powered by a desktop power supply, takes the analog output of the photosensor and converts the signal to an eight-bit binary value. These eight bits are displayed on eight LEDs on the board from least-significant bit to most-significant bit. Figure 4 is the circuit schematic of the detection device. The

detection device is then attached to the electric circuit. Figure 5 shows a prototype of the electronic detection device setup with the chip and agent plumbed into the chip. After testing the flow of water through their chip to explore pumping and capillary valving at the micron level, the students are ready to calibrate their device. For calibration, they are provided a 1000 PPM stock fluorescein solution and are required to make 250 PPM and 500 PPM calibration solutions by dilution. The binary output from the detector is recorded for each of four concentrations of fluorescein (0 PPM [DI water], 250 PPM, 500 PPM, and 1000 PPM). Between samples, distilled deionized water is flushed using the syringe to displace the sample from the detection well. Using these results, they then prepare a calibration curve from which an unknown sample concentration can be determined.

In the ninth lab session, the students perform a final test with unknown concentrations of fluorescein solution. Five different unknowns are provided but each team is only required to analyze three (the rest are available for bonus points). The accuracy of properly calibrated student devices falls in the range of $\pm 3\text{-}30\%$, depending on factors such as device sealing, cleanliness, consistently filled detection wells, consistent chip-detector orientation, and general attention to detail of the individual student teams. Certificates and small cash awards (made available through corporate donations to

the First-Year Engineering Program) are given to the top two teams with the best chip performance (accuracy); the team with the best project notebook; and the team giving the best oral presentation.

Nanotechnology Teaching Modules

Most of the lab activities are not truly nanoscale due to the lack of access to the major research instrumentation required (*e.g.*, electron beam lithography) and the associated costs. Students are, however, introduced to current and future applications of micro- and nanotechnology and the relative length scales of macro-, micro-, and nano-systems via multimedia presentation. This is intended to help the students to connect to the project on the first day of class. Moreover, the students are provided with six teaching modules of approximately six pages in length each, to discuss and explore nanotechnology issues related to the hands-on activities they perform in the lab. Table 2 lists these modules by topic, author, the respective affiliation of the author, and a brief synopsis of each. Discussion questions addressing the content of these modules are assigned for inclusion in lab memos and reports.

Nanotechnology Research Laboratory Tours

Lab tours are conducted by faculty and graduate researchers specifically recruited to demonstrate their nanotechnology research facilities to the freshman students. There are nine tours scheduled over a two-week period, allowing one lab section to work on the "Circuits I" lab while the other section tours research facilities during the third- and fourth-week lab sessions. A summary of the facilities toured and the corresponding topics covered in the tours is provided in Table 3. These tours enhance the students' overall experience and provide direct exposure to ongoing nanotechnology research. Many tour guides provide handouts and access to other information as well as visual aids for use by the student teams in their oral presentations at the end of the quarter. Oral presentations on their projects and lab tours are given in the tenth and final lab. Although each lab group only tours a single facility, the final class laboratory period is devoted to oral presentations where each group gives an 8-minute talk on the lab they visited, thus exposing the remainder of the class to the lab they experienced. The oral presentations also address the student designs and testing results and issues. The student teams are expected to discuss the relevance of the formal research conducted at the on-campus facilities in regards to their own design-build projects.

Although the design and fabrication techniques employed by the students represent the state of microscale research from as recently as the mid- to late 1990s, it is important to show the students how their work in microfabrication and design is analogous to current nanotechnology research. Both the Nanotechnology Teaching Modules and the lab tours provide a bridge from the students' hands-on lab activities and their associated assignments to the current research and pioneering efforts in the field of nanotechnology.

STUDENT RESPONSE

Midterm examinations with identical test content written by instructors uninvolved in this project were identically proctored during the 2004 academic year. A comparison of the mean scores of students in the pilot course vs. the remainder of the population in the standard course yielded statistically insignificant differences. This suggests that substituting a nontraditional design-build lab project for the existing electro-mechanical design-build project does not adversely affect students' learning of engineering fundamentals.

In the pilot course, the students' increases in knowledge and understanding of nanotechnology-related concepts during the quarter is indicated by their improved performance as they progressed from the preliminary queries of the first lab assignment, through the quizzes, to the nanotechnology-related questions on the final exam. Their enhanced grasp of nanotechnology and microfabrication concepts is also evident in their final project documentation and oral presentations. This suggests that first-year engineering students in an introductory engineering course can learn nanotechnology fundamentals and can apply basic microfabrication technology.

Although baseline results were not available for comparison, an overwhelming majority of students surveyed in the Spring 2004 version of the pilot course indicated interest in some form of research, although only two were actually involved at that early point in their studies. For some, this awareness of and interest in research may have been sparked by the students' involvement in the nanotechnology and microfabrication course.

The students also provided generally positive responses when asked about the connectedness of the various nanotechnology-related activities. A majority of students indicated that they felt the combinations of nanotechnology teaching modules, lab tours, and lab experiences provided a strong, integrated learning experience.

There is also an ongoing longitudinal study tracking student pursuits academically and professionally. Results of this study will be published in the future. Anecdotally, students have written members of the instructional team of this course thanking them for their experiences in the design-build and project-management activities, citing these as helpful with later coursework and in securing summer engineering internships. Other students have stated that this course has either fostered new interest or confirmed their existing interest in research, nanotechnology, and chemical engineering. Still other students have, after taking this course, applied and been selected to participate in National Nanotechnology Initiative (NNI) summer programs at respected institutions.

CONCLUSIONS

The successful implementation and standardization of the LOC design-build project with a nanotechnology component for first-year engineering students is promising in that it shows

TABLE 2
Nanotechnology Teaching Modules, Authors, and Affiliations

Module	Topic	Author	Affiliation	Summary
1	Top-Down vs. Bottom-Up Nanomanufacturing	Derek J. Hansford	Biomedical Engineering Program; Department of Materials Science & Engineering	Methods, strengths, and limitations of fabricating nanometer-scale structures using Top-down methods (lithography and patterning) compared to bottom-up methods (self-assembly and selective growth); current uses of both nanomanufacturing techniques.
2	Molecular Self-Assembly	James F. Rathman	Department of Chemical and Biomolecular Engineering	Role of intermolecular forces in molecular self-assembly of amphiphilic molecules; formation of 3-D structures by self-assembly in solution; surface tension and the formation of 2-D structures by self-assembly at interfaces.
3	Nano-Structured Ceramics for Chemical Sensing	Sheikh A. Akbar	Department of Materials Science & Engineering	The emerging field of nano-ceramics and nanotechnology; some potential applications with an emphasis on chemical sensors; the challenges and opportunities in this evolving area.
4	Polymer Processing at the Nanoscale	L. James Lee	Department of Chemical and Biomolecular Engineering	The emerging field of nanoscale manufacturing of polymeric materials; state-of-the-art mold (master) making and replication techniques; challenges and opportunities in this evolving area.
5	Nanofluidics	A. Terrence Conlisk	Department of Mechanical Engineering	How nanofluidics differs from traditional fluid mechanics, with emphasis on fluid flow in a tube or channel.
6	Nanotechnology for Drug Delivery	Derek J. Hansford	Biomedical Engineering Program; Department of Materials Science & Engineering	Concepts in drug delivery, including tissue targeting, biomolecular markers, and reasons to use controlled release; basic concepts of nanoparticles and why they are useful for drug delivery; understanding the differences of classes of nanoparticles.

TABLE 3
Nanotechnology Research Facility Tours

Facility Toured	Tour Topic
Ohio MicroMD Laboratory Cleanroom Facility (now Nanotech West)	Medical and biomedical applications; silicon, polymer characterization; photolithography; biohybrid processing.
Micro/Nanoscale Welding Laboratories	Nanoindenter, Nd:YAG laser micromachining.
Nanoscale Metrology and Measurement Lab	Laser-guided magnetic suspension stage; dynamic modeling with ATM tip-cantilever system.
Microfabrication Laboratory	Replication of microstructures for microfluidics, sensing, tissue engineering, and drug delivery; structural testing; microfluidic testing; fluorescence testing with microscope.
Atomic Force Microscopy Lab	Use of Atomic Force Microscopy for surface topography at the atomic length scale.
Electronics Cleanroom Manufacturing Facility	Silicon processing; photolithography equipment and methods; mask aligners; spinner; thermal evaporator.
Nanoelectronics and Optoelectronics Lab	Dielectric deposition, hydrogen processing, and etching; electron beam evaporation; filament evaporation; ellipsometer; photolithography; annealing, oxidation and diffusion furnaces; pulsed laser deposition.
Semiconductor Epitaxy and Analysis Laboratory	Applications in optoelectronics, photovoltaics, electronics, and integrated systems.

that traditional boundaries of electro-mechanical design-build projects can be expanded to include new and cutting-edge technologies only recently trickled down from the graduate research arena to the undergraduate classroom. It is important to expose new engineering students early to these new technologies as there is a projected need for researchers and professionals in the burgeoning field of nanotechnology. It is

yet to be confirmed, but this early exposure can potentially foster student interest in careers in nanotechnology, thus helping fulfill future demand for qualified scholars and professionals. The standardization (after revisions) and expansion of this offering to more course sections illustrates that the importance of nanotechnology in research and education can be addressed at the early undergraduate level.

It is shown that nanotechnology can fit in an introductory engineering program. The comparable performance of the pilot and nonpilot students on identically proctored and independently graded exams supports this statement. In addition, the online journal and assessment responses from the students in the pilot course do not stand out from comments provided by the nonpilot students.

ACKNOWLEDGMENTS

This project was supported financially by the National Science Foundation (EEC- 0304469) and the First-Year Engineering Program in the College of Engineering at The Ohio State University. The authors also acknowledge the contributions of Professors Derek Hansford (Biomedical Engineering, Materials Science and Engineering) and L. James Lee (Chemical and Biomolecular Engineering) to the success of the project.

REFERENCES

1. <<http://www.nano.gov/html/facts/whatIsNano.html>> Accessed Aug. 14, 2004
2. Al-Holou, N., et al., "First-year Integrated Curricula: Design Alternatives and Examples," *J. Eng. Educ.*, **88**(4): 435 (1999)
3. Finelli, C.J., A. Klinger, and D.D. Budny, "Strategies for Improving the Classroom Environment," *J. Eng. Educ.*, **90**(4), 491 (2001)
4. Guilbeau, E.J., and V.B. Pizziconi, "Increasing Student Awareness of Ethical, Social, Legal, and Economic Implications of Technology," *J. Eng. Educ.*, **87**(1) 35 (1998)
5. Mourtos, N.J., "The Nuts and Bolts of Cooperative Learning in Engineering," *J. Eng. Educ.*, **86**(1) 35 (1997)
6. Merrill, J.A., "The Role of Outcomes Assessment in a Large-Scale First-Year Engineering Environment," in *Proceedings of the 2002 ABET Conference on Outcomes Assessment* (2002)
7. Desai, T.A., and R.L. Magin, "A Cure for Bioengineering? A New Undergraduate Core Curriculum," *J. Eng. Educ.*, **90**(2) 231 (2001)
8. Choudhury, J., et al., "Initiating a Program in Nanotechnology Through a Structured Curriculum," in *Proceedings of the 2003 IEEE International Conference on Microelectronic Systems Education* (2003)
9. Uddin, M., and A.R. Chowdhury, "Integration of Nanotechnology Into the Undergraduate Engineering Curriculum," in *International Conference on Engineering Education*, Oslo, Norway (2001)
10. Hersam, M.C., M. Luna, and G. Light, "Implementation of Interdisciplinary Group Learning and Peer Assessment in a Nanotechnology Engineering Course," *J. Eng. Educ.*, **93**(1) 49 (2004)
11. Adams, J.D., B.S. Rogers, and L.J. Leifer, "Microtechnology, Nanotechnology, and the Scanning-Probe Microscope: An Innovative Course," *IEEE Transactions on Education*, **47**(1) 51 (2004)
12. Adams, J.D., B.S. Rogers, and L.J. Leifer, "Effective technology transfer to the undergraduate and graduate classroom as a result of a novel Ph.D. program," *IEEE Transactions on Education*, **47**(2) p. 227-231 (2004)
13. Lai, S., S. Wang, J. Luo, L.J. Lee, S.-T. Yang, and M.J. Madou, "Design of a Compact Disk-like Microfluidic Platform for Enzyme-Linked Immunosorbent Assay," *Analytical Chemistry*, **76**(7), 1832-1837 (2004)
14. Madou, M.J., L.J. Lee, S. Daunert, S. Lai, and C.-H. Shih, "Design and Fabrication of CD-like Microfluidic Platforms for Diagnostics: Microfluidic Functions," *Biomedical Microdevices*, **3**(3) 245 (2001)
15. Yang, Y., L.J. Lee, and K.W. Koelling, "Structure Evolution in Polymer Blending Using Microfabricated Samples," *Polymer*, **45**(6) 1959-1969 (2004)
16. Lee, L.J., M.J. Madou, K.W. Koelling, S. Daunert, S. Lai, and C.G. Koh, et al., "Design and Fabrication of CD-Like Microfluidic Platforms for Diagnostics: Polymer-Based Microfabrication," *Biomedical Microdevices*, **3**(4) 339 (2001) □

Interdisciplinary Learning for ChE Students

FROM ORGANIC CHEMISTRY SYNTHESIS LAB TO REACTOR DESIGN TO SEPARATION

MATT ARMSTRONG, RICHARD L. COMITZ, ANDREW BIAGLOW, RUSS LACHANCE, AND JOSEPH SLOOP
United States Military Academy • West Point, NY

Interdisciplinary learning and curriculum integration are two very valuable methods to develop our future leaders. Klein (1990) defines interdisciplinary learning as the synthesis of two or more disciplines, establishing a new level of discourse and integration of knowledge.^[1] Curriculum integration implies restructuring learning activities to help students build connections between topics.^[2] Since our main goal at the United States Military Academy is to develop

multidimensional problem solvers, it only makes sense that we as an institution try to integrate interdisciplinary learning into more classes. We saw a perfect opportunity to do this in the Department of Chemistry and Life Science.

At the United States Military Academy, the Chemical Engineering curriculum has the students enrolled in three courses simultaneously in the Spring semester of their third year—Organic Chemistry II, Separation Processes, and

Major Matthew Armstrong teaches CH101/102, General Chemistry, CH 364 Chemical Reaction Engineering, CH 489/CH490 Individual Research, and also serves as the Department S4. He received his B.S. and M.S. in chemical engineering from Rensselaer Polytechnic Institute in Troy, NY.



Major Rich Comitz taught CH101/102, General Chemistry last year. He is now the assistant course director for CH 383/384, Organic Chemistry I & II, and CH 489/CH490 Individual Research. He received his B.S. in chemistry at the United States Military Academy, at West Point, NY, and his M.S. in chemistry at the Florida Institute of Technology.

Dr. Andrew Biaglow teaches chemistry core and elective courses. He is

the director of the Chemical Engineering Program, and responsible for establishing a research program in Chemical Reaction Engineering. Dr. Biaglow is a member of the International Zeolite Association, the American Institute of Chemical Engineers, and the American Society of Engineering Educators. He conducts research on reaction pathways and intermediates in solid-catalyzed reactions. He is a member of the Materials Research Society, New York Catalysis Club, and the American Chemical Society.

Colonel Russ Lachance is an Academy Professor supporting the Chemical Engineering Program. His teaching responsibilities include all chemical engineering and general chemistry courses. Col. Lachance is the Head Academic Counselor and the ABET coordinator for the Department. He serves on the ABET Committee and the Faculty Council, and is the Officer-in-Charge of the Cadet Spirit Band and Spirit Group. He is also the PME2 Team Leader for Company B4.

Lieutenant Colonel Joseph Sloop teaches CH383/384, Organic Chemistry I & II. Lieutenant Colonel Sloop's scientific interests include heterocycle synthesis, substituent effects on reactivity in organic systems, and magnetochemistry. He is a member of the American Chemical Society, Phi Lambda Upsilon, Phi Kappa Phi, Gamma Sigma Epsilon, and the Chemical Corps regiment.

Chemical Reaction Engineering (Figure 1).

In Organic Chemistry II, students learn the theory behind organic reactions as well as do bench-top experiments that show the practical applications of this theory. In Chemical Reaction Engineering, the students learn how to scale the bench-top experiments up and to design reactors to perform these experiments at industrial levels. Finally, in Separation Processes, students learn how to take this scaled-up process and improve the yield and purity of the final product. This juxtaposition allowed us to simultaneously study a common reaction, the Friedel-Crafts alkylation, in each of the respective classes. During one of the laboratory experiments in Organic Chemistry II, the students performed a reaction in which two products are formed. They were then tasked to separate these two products, but because of time and instrumentation constraints, were mostly unsuccessful. For chemical engineering students, it seems a natural progression to explore solutions to this problem in the context of a chemical separations issue and reactor design. Since these students often take organic chemistry, chemical reactor design, and chemical separations together, an interdisciplinary project such as this provides a practical application to bridge the theory developed in all three courses with an experimental challenge. With our sequencing of courses we have provided our students with an approach that closely resembles the reality of the actual design process, to include the ability to use chemical engineering software in an earlier stage of the development process.

Another significant added benefit was a connection we began to draw between the engineering design process (Figure 2) and the Military Decision Making Process (MDMP) (Figure 3) taught in third-year military science class. Both processes first define the problem or the mission by examining facts, assumptions, and specified/implied/critical tasks. Both processes then design alternatives and model or test those alternatives so they can be analyzed and compared. Finally, both processes enable us to arrive at a reasonable decision and both are iterative in nature with feedback loops to further refine the design or plan. While this interdisciplinary project was designed to show our students the connections between organic chemistry, reaction engineering, and separations, we were able to draw multiple connections across many aspects

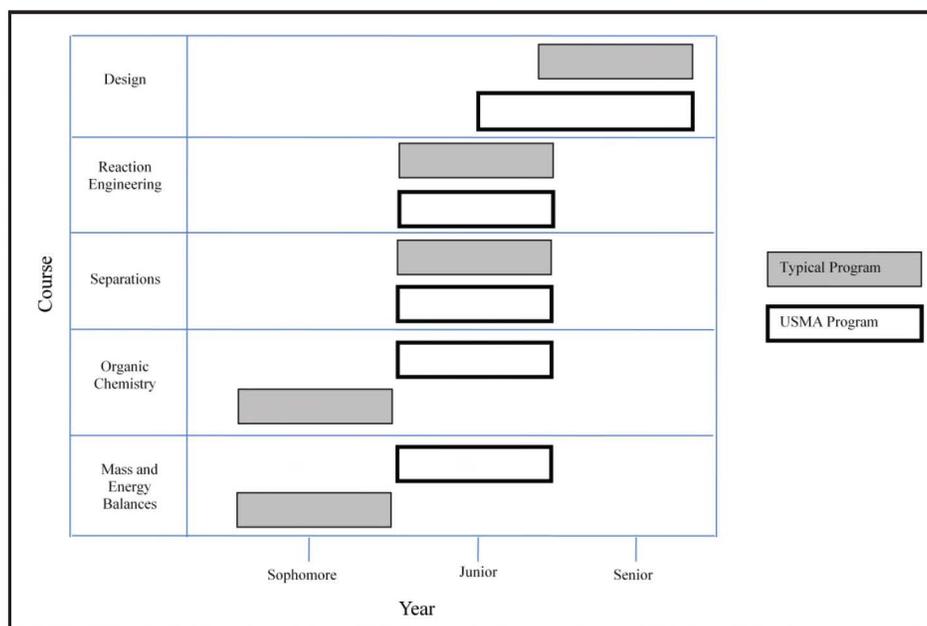


Figure 1. Chemical Engineering Program order of courses.

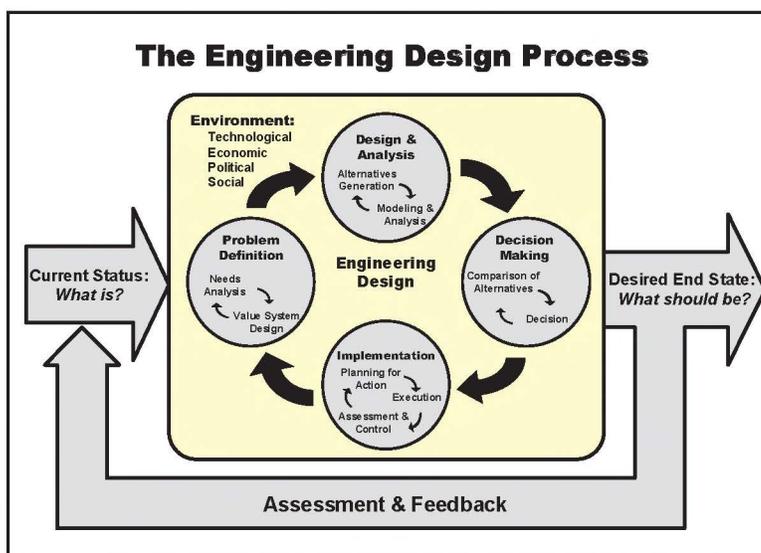


Figure 2. The engineering design process.^[3]

of our curriculum like the case of engineering design and military science.

BACKGROUND

The Friedel-Crafts reaction is used in laboratory synthesis as well as in industry in the synthesis of ethylbenzene and its derivatives as an intermediate to make styrene monomers.^[3] Therefore, this reaction was a good choice to integrate several different courses.

Laboratory experiments conducted during the second semester of organic chemistry generally illustrate practical application of topics covered in lecture. A convenient Frie-

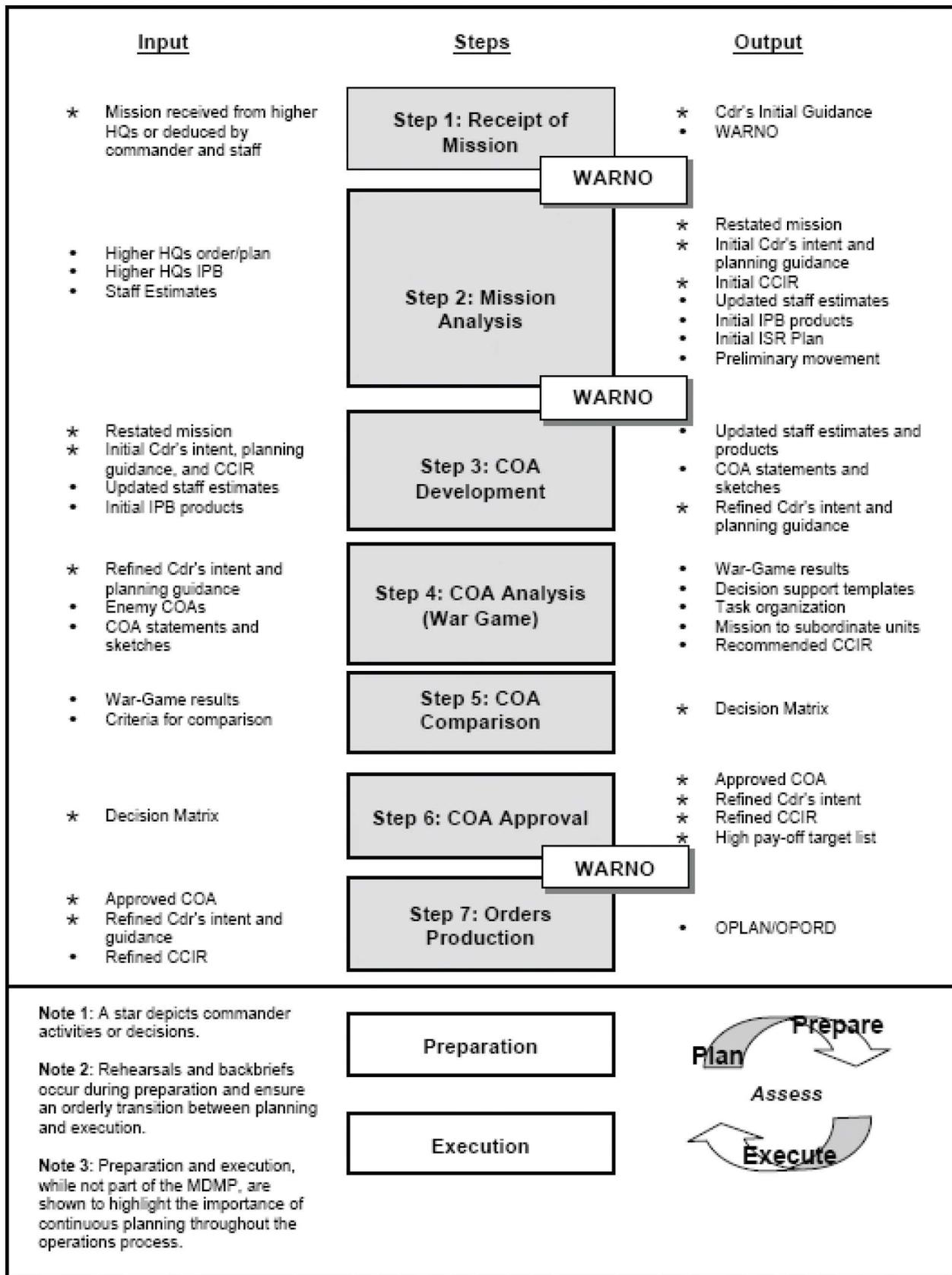


Figure 3. The Military Decision Making Process.^[4]

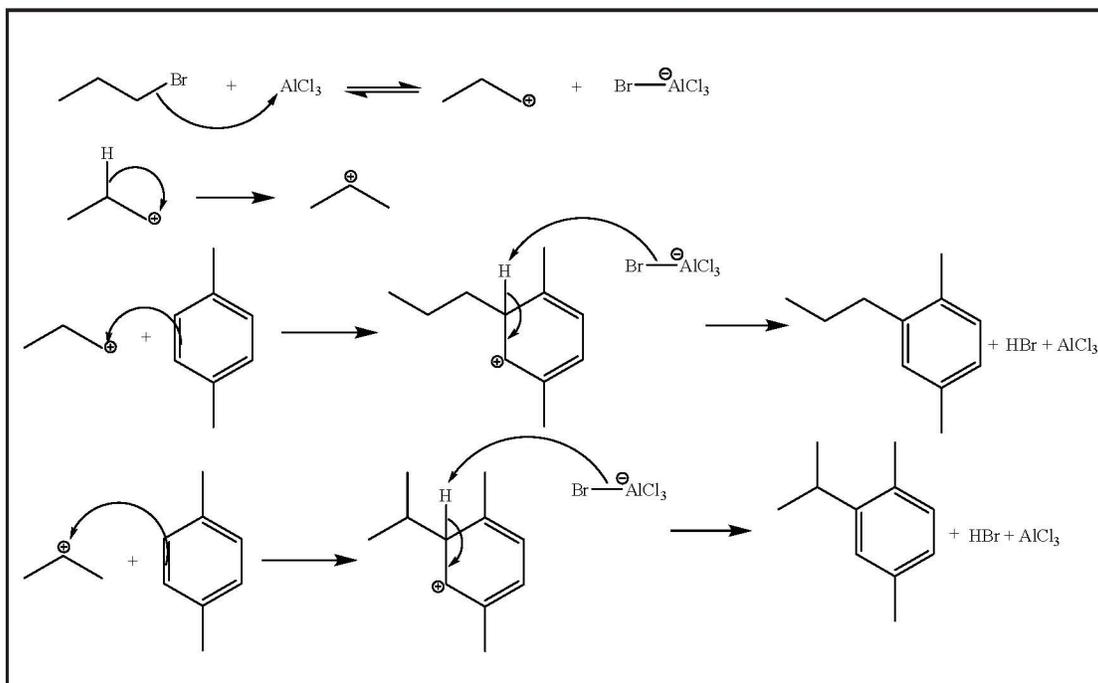


Figure 5. Friedel-Crafts alkylation of *p*-xylene mechanism.^[5]

where $M = C_{B_0}/C_{A_0}$, X = conversion, k = reaction rate constant, reactant A = *p*-xylene, B = 1-bromopropane.

The implication of this result show that a plot of $\ln(C_B/C_A)$ versus time will yield a straight line if indeed the reaction is second order, and first order with respect to each reactant. The intercept will equal M , and the slope will be equal to $(C_{B_0} - C_{A_0})k_{tot}$.

EXPERIMENTAL

Three experiments were set up identically at temperatures of 295.5 K, 311 K, and 333 K. To 15.0 mL of *p*-xylene was added 1.00 g of $AlCl_3$. The resulting mixture was allowed to stir while 8.0 mL of 1-bromopropane was added dropwise over a period of 5-10 minutes. At two-minute intervals, a microliter sample was extracted from the reaction vessel, quenched with water, and diluted with diethyl ether. After removal of the aqueous layer, the samples were dried over sodium sulfate. The samples were examined in the Gas Chromatograph/MS to determine the concentrations of reactants and products in each sample.

The reaction progress was monitored by gas chromatography, and the kinetic data recorded in Table 1. By plotting the concentration data from the gas chromatograph found in Table 1, it is possible to calculate the k_{tot} .^[4]

With that information and the average ratio of products at each time step it is possible to calculate k_1 and k_2 with the following two equations:^[4]

$$k_{tot} = k_1 = k_2 \quad (4)$$

$$\left(\frac{C_n - \text{propyl}}{C_{\text{isopropyl}}} \right)_{AVE} = \frac{k_1}{k_2} \quad (5)$$

When all of the reaction rate constants were determined it was then possible to solve for individual frequency factors, k_0 , and activation energies, E_a , using the Arrhenius relationship:

$$k = k_0 e^{-E_a/RT} \quad (6)$$

Plotting $\ln k$ vs. $1/T$, the slope of this line is $-E_a/R$, and the y intercept is k_0 , thus permitting the calculation of both k_0 and E_a for each parallel reaction, and the overall reaction.

The activation energy values and frequency factors are critical to model and scale up the reaction using ChemCad. This entire process was expected to be executed by each student, thus reinforcing the derivation of a concentration vs. time model. Each student had to demonstrate mastery of this process at a desk-side briefing to the instructor before using ChemCad. Upon successful calculation of the reaction rate constants, students were allowed to start the scale-up modeling with ChemCad.

With this data, it was now possible to establish the appropriate kinetic relationships in ChemCAD. The students then used ChemCad to search the most economically feasible reactor design. A cursory analysis of the data yielded an appropriate plot of $1/-r_A$ vs. X_A . Analysis of the plot makes it clear that the best reactor design to minimize volume should be a plug flow setup. Using Mathematica, the mean residence time and

For chemical engineering students, it seems a natural progression to explore solutions . . . in the context of a chemical separations issue and reactor design. Since these students often take organic chemistry, chemical reactor design, and chemical separations together, an interdisciplinary project such as this provides a practical application to bridge the theory developed in all three courses with an experimental challenge.

volume for the initial guess can be estimated. Questions left to resolve are reactor volume, heat duty, and isothermal vs. adiabatic operation. Students were free to explore various reactor networks, such as parallel vs. series reactors and use of recycle. Students were given latitude to explore other unique strategies using ChemCad.

CHEMICAL SEPARATIONS DESIGN PROJECT

The chemical separations design phase of this interdisciplinary project was fairly open ended. The students could use any combination of separations schemes to achieve 90% purity of all components in the system (feed, catalyst, products) and then attempt to achieve a 95% n-propyl-p-xylene product stream. This open-ended approach forced the students to consider all aspects of a realistic separation problem that originated in their organic chemistry lab and that they might see in industry. At first, the students were intimidated because a detailed solution required knowledge beyond their current level, but they eventually enjoyed working on this problem because it truly challenged them to think.

Like the reactor design project, our students began the separations design project by gathering property information. When they could not find certain property information for some of the compounds they quickly learned how to make reasonable approximations and assumptions. We advised the students that a critical task in their design was to determine the best separation technique for each of the components and decide on the most logical sequencing of those techniques. Based on the available property information, most student teams chose to flash off HBr, extract AlCl₃ using water, and use a series of distillation columns to purify the remaining components. Much like a real-world design process, however, we forced each team to consider at least two different separation sequences and compare and contrast them. In this way our students learned a great deal about separations processes.

The separations design project also used ChemCad software as the vehicle for the design. Most student teams attempted to jump right into ChemCad without much preparatory analysis, and their initial results clearly emphasized the importance of choosing a reasonable thermodynamic model, and making some preliminary estimates. While students will be expected to use thermodynamic modeling in greater depth later in their curriculum, this exercise served as an excellent tool to emphasize the importance of material yet to come. As a result of creating, manipulating and running ChemCad examples, all students in-

creased their ChemCad proficiency, which is a critical software thread for our entire chemical engineering program.

One design team exceeded our expectations for a truly integrated design solution. This team combined their reactor design with their separations design in the same process flow sheet. Although we expected separate reactor and separations designs from these third-year students in these separate courses, this team made the logical leap and combined the designs to achieve some additional efficiencies. Figure 7 depicts their ChemCad design flow sheet which incorporates a recycle stream for unconverted reactants.

ANALYSIS OF RESULTS

To analyze the results the students were given a quiz at the beginning of the semester consisting of representative questions from the organic chemistry, chemical reaction engineering, and separations disciplines. The same quiz was then re-administered at the end of the semester to see if there was improvement, and retention of knowledge. These results are in Table 3.

In addition to this the students were asked the following questions regarding their individual experiences with the design project at the end of the semester. These questions were answered on a scale of 1 to 5, where 1 represented the most positive feedback and 5 was the least positive. These questions are listed in Table 4 accompanied by the averaged response. A comparison will be made of final examination results from AY06-02 to AY07-2 in the chemical reaction engineering course, to see the impact this had on performance. Although the data only showed a small increase, the students overall exhibited more confidence when approaching these type of problems in other courses.

From the results, it is clear that the design experience had a positive outcome in terms of mastery of the material. The students' responses to the questions were also quite positive. We will conduct the same approach in the years to come and continue to gather data.

TABLE 2
Rate Constant (k) vs. Temperature (K)

Reaction #1 (isopropyl)		Reaction #2 (n-propyl)	
k ₁	T	k ₂	T
0.0296	333	0.00653	295.5
0.0050	311	0.0085	311
0.0029	295.5	0.035	333

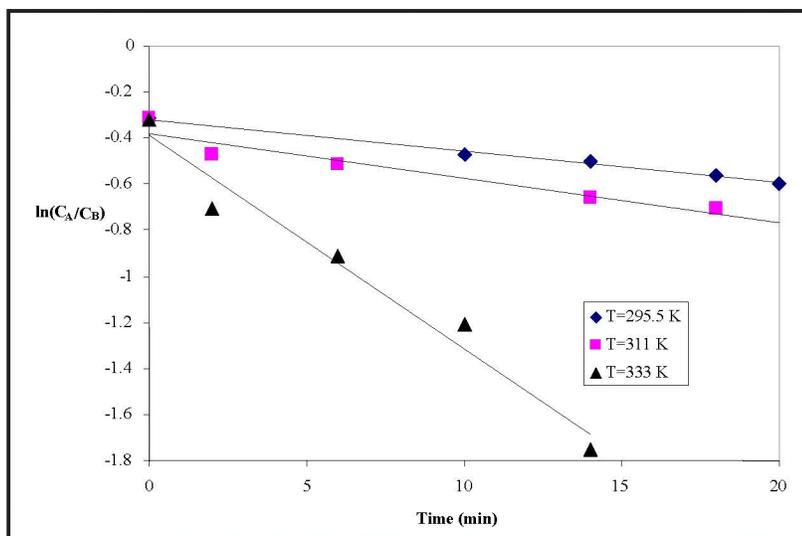


Figure 6. Concentration vs. time plot.

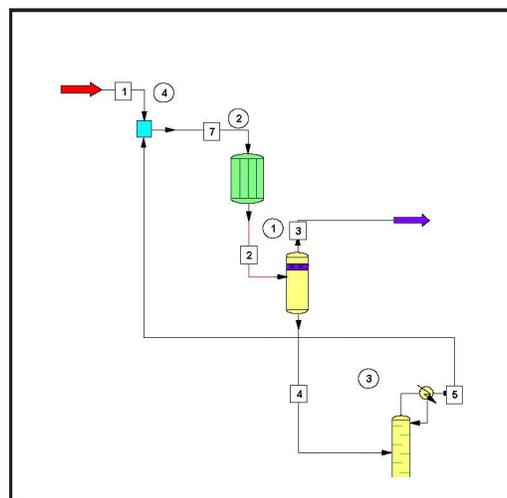


Figure 7. Student team's fully integrated reactor and separations design proposal.

TABLE 3
Quiz Results

Question	Pre-Project:			Post-Project:		
	Question #	Correct	Incorrect	Question #	Correct	Incorrect
What is a Friedel Crafts alkylation?	1	5	6	1	7	4
Give an example of one.	2	3	8	2	9	2
Method of calc. k_0 and E_A .	3	2	9	3	8	3
Method of k_1 , k_2 calc. parallel rxns.	4	0	11	4	7	4
Can k_1 , k_2 be found graphically?	5	0	11	5	2	9
Give two ways to separate gas and liquid phases.	6	8	3	6	10	1
Give two ways to separate two liquid phases.	7	8	3	7	10	1

TABLE 4
Questions Regarding Individual Experiences

Question Regarding Individual Experience	Ave Response
1. Was this design project useful in terms of helping the learning process?	1.64
2. Was this design project helpful to wrap up the course material at end of semester?	1.73
3. Did this design project aid your learning in organic chemistry and separations?	2.27
4. Would you recommend this project format next year?	2.09
5. Did you like the design project?	2.55
6. Do you think the design experience helped your Term End Exam preparation?	2.09

CONCLUSION

This idea started out as merely a project for our Chemical Reaction Engineering course, but evolved into a novel educational approach to chemical engineering curriculum development using a technique closely paralleling the actual industry design process. From our results, it is apparent that this is indeed a valid approach. The experience allowed the students to approach the problem as a design engineer in industry would, as well as use the problem-solving techniques previously discussed. Additionally, the students were able to use the chemical engineering software earlier by using the kinetic data given to them. We intend to use this technique again, and recommend it fully to other programs. In fact, the project is in its second iteration and has evolved to include other factors such as cost optimization and environmental impact. As this project becomes a

more prominent feature of our program, we will give the students less data, requiring them to decide what information is needed.

REFERENCES

1. Eves, R.L., et al., "Integration of Field Studies and Undergraduate Research Into an Interdisciplinary Course," *J. College Science Teaching*, **36**(6) 22 (May/June 2007)
2. The Foundation Coalition "Curriculum Integration-Students Linking Ideas across Disciplines," <<http://www.foundationcoalition.org/publications/brouchures/curriculum-integration.pdf>>
3. *CE300 Course Book*, USMA (20 June 2007)
4. *FM 5-0*, Army Planning and Orders Production (January 2005)
5. Gilbert, J.C., and S.F. Martin, *Experimental Organic Chemistry A Miniscale and Microscale Approach*, 4th Ed., Thomson Brooks, Cole, CA (2006)
6. Levenspiel, O., *Chemical Reaction Engineering*, 3rd Ed., John Wiley and Sons Inc., New York, (1999) □

Random Thoughts . . .

THE 10 WORST TEACHING MISTAKES

I. MISTAKES 5–10

RICHARD M. FELDER

North Carolina State University

REBECCA BRENT

Education Designs, Inc.

Like most faculty members, we began our academic careers with zero prior instruction on college teaching and quickly made almost every possible blunder. We've also been peer reviewers and mentors to colleagues, and that experience on top of our own early stumbling has given us a good sense of the most common mistakes college teachers make. In this column and one to follow we present our top ten list, in roughly increasing order of badness. Doing some of the things on the list may occasionally be justified, so we're not telling you to avoid all of them at all costs. We *are* suggesting that you avoid making a habit of any of them.

Mistake #10. When you ask a question in class, immediately call for volunteers.

You know what happens when you do that. Most of the students avoid eye contact, and either you get a response from one of the two or three who always volunteer or you answer your own question. Few students even bother to think about the question, since they know that eventually someone else will provide the answer.

We have a suggestion for a better way to handle questioning, but it's the same one we'll have for Mistake #9 so let's hold off on it for a moment.

Mistake #9. Call on students cold.

You stop in mid-lecture and point your finger abruptly: "Joe, what's the next step?" Some students are comfortable under that kind of pressure, but many could have trouble thinking of their own name. If you frequently call on students without giving them time to think ("cold-calling"), the ones who are intimidated by it won't be following your lecture as much as praying that you don't land on them. Even worse, as soon as you call on someone, the others breathe a sigh of relief and stop thinking.

A better approach to questioning in class is *active learning*.^[1] Ask the question and give the students a short time to come up with an answer, working either individually or in small groups. Stop them when the time is up and call on a few to report what they came up with. *Then*, if you haven't gotten the complete response you're looking for, call for volunteers. The students will have time to think about the question, and—unlike what happens when you always jump directly to volunteers (Mistake #10)—most will try to come up with a response because they don't want to look bad if you call on them. With active learning you'll also avoid the intimidation of cold-calling (Mistake #9) and you'll get more and better answers to your questions. Most importantly, real learning

Richard M. Felder is Hoechst Celanese Professor Emeritus of Chemical Engineering at North Carolina State University. He is co-author of *Elementary Principles of Chemical Processes* (Wiley, 2005) and numerous articles on chemical process engineering and engineering and science education, and regularly presents workshops on effective college teaching at campuses and conferences around the world. Many of his publications can be seen at <www.ncsu.edu/felder-public>.



Rebecca Brent is an education consultant specializing in faculty development for effective university teaching, classroom and computer-based simulations in teacher education, and K-12 staff development in language arts and classroom management. She codirects the ASEE National Effective Teaching Institute and has published articles on a variety of topics including writing in undergraduate courses, cooperative learning, public school reform, and effective university teaching.

© Copyright ChE Division of ASEE 2008

will take place in class, something that doesn't happen much in traditional lectures.^[2]

Mistake #8. Turn classes into PowerPoint shows.

It has become common for instructors to put their lecture notes into PowerPoint and to spend their class time mainly droning through the slides. Classes like that are generally a waste of time for everyone.^[3] If the students don't have paper copies of the slides, there's no way they can keep up. If they have the copies, they can read the slides faster than the instructor can lecture through them, the classes are exercises in boredom, the students have little incentive to show up, and many don't.

Turning classes into extended slide shows is a specific example of:

Mistake #7. Fail to provide variety in instruction.

Nonstop lecturing produces very little learning,^[2] but if good instructors never lectured they could not motivate students by occasionally sharing their experience and wisdom. Pure PowerPoint shows are ineffective, but so are lectures with no visual content—schematics, diagrams, animations, photos, video clips, etc.—for which PowerPoint is ideal. Individual student assignments alone would not teach students the critical skills of teamwork, leadership, and conflict management they will need to succeed as professionals, but team assignments alone would not promote the equally important trait of independent learning. Effective instruction mixes things up: boardwork, multimedia, storytelling, discussion, activities, individual assignments, and group work (being careful to avoid Mistake #6). The more variety you build in, the more effective the class is likely to be.

Mistake #6. Have students work in groups with no individual accountability.

All students and instructors who have ever been involved with group work know the potential downside. One or two students do the work, the others coast along understanding little of what their more responsible teammates did, everyone gets the same grade, resentments and conflicts build, and the students learn nothing about high-performance teamwork and how to achieve it.

The way to make group work work is *cooperative learning*, an exhaustively researched instructional method that effectively promotes development of both cognitive and interpersonal skills. One of the defining features of this method is *individual accountability*—holding each team member accountable for the entire project and not just the part that he or she may have focused on. References on cooperative learning offer suggestions for achieving individual account-

ability, including giving individual exams covering the full range of knowledge and skills required to complete the project and assigning individual grades based in part on how well the students met their responsibilities to their team.^[4, 5]

Mistake #5. Fail to establish relevance.

Students learn best when they clearly perceive the relevance of course content to their interests and career goals. The “trust me” approach to education (“*You may have no idea now why you need to know this stuff but trust me, in a few years you’ll see how important it is!*”) doesn’t inspire students with a burning desire to learn, and those who do learn tend to be motivated only by grades.

To provide better motivation, begin the course by describing how the content relates to important technological and social problems and to whatever you know of the students’ experience, interests, and career goals, and do the same thing when you introduce each new topic. (If there are no such connections, why is the course being taught?) Consider applying inductive methods such as guided inquiry and problem-based learning, which use real-world problems to provide context for all course material.^[6] You can anticipate some student resistance to those methods, since they force students to take unaccustomed responsibility for their own learning, but there are effective ways to defuse resistance^[7] and the methods lead to enough additional learning to justify whatever additional effort it may take to implement them.

Stay tuned for the final four exciting mistakes!

REFERENCES

1. Felder, R.M., and R. Brent, “Learning by Doing,” *Chem. Engr. Education*, **37**(4), 282 (2003) <www.ncsu.edu/felder-public/Columns/Active.pdf>
2. Prince, M., “Does Active Learning Work? A Review of the Research,” *J. Engr. Education*, **93**(3), 223 (2004) <www.ncsu.edu/felder-public/Papers/Prince_AL.pdf>
3. Felder, R.M., and R. Brent, “Death by PowerPoint,” *Chem. Engr. Education*, **39**(1), 28 (2005) <www.ncsu.edu/felder-public/Columns/PowerPoint.pdf>
4. Felder, R.M., and R. Brent, “Cooperative Learning,” in P.A. Mabrouk, ed., *Active Learning: Models from the Analytical Sciences, ACS Symposium Series 970*, Chapter 4. Washington, DC: American Chemical Society (2007) <www.ncsu.edu/felder-public/Papers/CLChapter.pdf>
5. CATME (Comprehensive Assessment of Team Member Effectiveness), <www.catme.org>
6. Prince, M.J., and R.M. Felder, “Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases,” *J. Engr. Education*, **95**(2), 123 (2006) <www.ncsu.edu/felder-public/Papers/InductiveTeaching.pdf>
7. Felder, R.M., “Sermons for Grumpy Campers,” *Chem. Engr. Education*, **41**(3), 183 (2007) <www.ncsu.edu/felder-public/Columns/Sermons.pdf> □

All of the *Random Thoughts* columns are now available on the World Wide Web at
http://www.ncsu.edu/effective_teaching and at <http://che.ufl.edu/~cee/>

PEDAGOGICAL TRAINING AND RESEARCH IN ENGINEERING EDUCATION

PHILLIP C. WANKAT

Purdue University • West Lafayette, IN 47907-2100

Significant changes are occurring in the ways that engineering is taught and in our understanding of how students learn. Signs of this ferment include the changing publication requirements of the *Journal of Engineering Education (JEE)*,^[1,2] increased interest in teaching professors how to teach, National Academy of Engineering (NAE) studies on engineering education in the 21st century,^[3,4] the development of the NAE Center for the Advancement of Scholarship on Engineering Education (CASEE)^[5] and its development of the engineering education research portal AREE,^[6] the availability of funds for engineering education research from NSF including the National Engineering Education Colloquies^[7] that resulted in a national research agenda for engineering education,^[8] the development of numerous engineering education research centers,^[5] changes in ABET requirements,^[9] the development of Departments of Engineering Education at Purdue^[10] and Virginia Tech,^[11] the development of an engineering and science education department at Clemson,^[12] the development of an engineering and technology education department at Utah State,^[13] and an increasing number of chemical engineering departments that allow students to do their Ph.D. research on engineering education. After a short history of engineering education, we will discuss pedagogical training for all professors and research training for specialists in engineering education.

BRIEF HISTORY OF ENGINEERING EDUCATION IN THE UNITED STATES^[14]

The first engineering instruction in the United States occurred at the United States Military Academy at West Point,

New York, which was authorized by Congress in 1802. In 1819 Alden Partridge, a graduate and former instructor at West Point, founded the American Literary, Scientific, and Military Academy (now Norwich University) at Norwich, Vermont. The first civilian courses in engineering were taught at this academy. Shortly after this, in 1824, Stephen Van Rensselaer established the Rensselaer School (now Rensselaer Polytechnic Institute) at Troy, New York. The amount of engineering in the curriculum was gradually increased until the first degrees in civil engineering were granted in 1835.

The increasing development of canals and railroads increased demand for engineers, who were seen as necessary for economic development. This led to the opening of a number of engineering schools; however, many of these schools closed during the depression of the late 1830s and 1840s. A shortsighted lack of support of engineering education during lean economic periods has been repeated several times since then. After the depression ended, the westward expansion of the United States continued to increase the demand for engineers.



Phil Wankat has a joint appointment in Chemical Engineering and in Engineering Education at Purdue University. He has a B.S.ChE from Purdue, a Ph.D. from Princeton, and an M.S.Ed from Purdue. He is the Associate Editor of CEE.

© Copyright ChE Division of ASEE 2008

In 1862, Justin Morrill of Vermont succeeded in passing the seminal Morrill Land Grant Act that was then signed by President Lincoln. This act allowed the federal government to give the proceeds from the sale of federal land to the states for support of colleges to teach “agriculture and mechanical arts.” The act had little effect during the Civil War, and by 1865 there were only approximately 20 engineering schools in the United States, including several dormant schools in the South. After the war, engineering education boomed and by 1872 there were 70 engineering colleges. Some of the land grant programs were at existing state universities (*e.g.*, Minnesota, Rutgers, and Wisconsin), others were formed by converting existing small private colleges into state universities (*e.g.*, Auburn and Virginia Tech), while some were totally new institutions (*e.g.*, Purdue and Texas A&M). In 1890 the land grant schools were stabilized by the passing of the second Morrill Act that provided for annual appropriations.^[15] In this second law Morrill^[15] also tried to prevent spending federal funds in states where there was “a distinction of race or color.” Unfortunately, this intent to encourage integration was unsuccessful, and after numerous compromises the act permitted the development of separate land-grant institutions for blacks (*e.g.*, Tennessee State University and North Carolina A&T). They were supposed to be equal, but soon became unequal.^[15]

Another pattern has been the establishment, then closure, and occasionally reestablishment, of engineering colleges. Examples are the programs at the College of William and Mary, the Polytechnic College of Pennsylvania, the University of Alabama, and Harvard University.^[14] Money continues to have an effect on developments in engineering education.

The urge to develop new engineering disciplines is almost as old as the teaching of engineering. Military engineering was naturally the subject at West Point. Both Norwich and Rensselaer started teaching civil engineering. Mechanical engineering followed with the U.S. Naval Academy offering steam engineering in 1845, and the first mechanical engineering degrees awarded by the Polytechnic College of Pennsylvania in 1854. The Polytechnic College of Pennsylvania also instituted mining engineering in 1857 followed by the Columbia University School of Mines in 1864. Electrical engineering, introduced at MIT in 1882, very rapidly flourished. The first course in chemical engineering was taught at MIT in 1888.^[16] Fledgling chemical engineering programs formed within chemistry departments at the University of Pennsylvania in 1892, Tulane University in 1894, the University of Michigan and Tufts University in 1898, and the Armour Institute of Technology (now Illinois Institute of Technology) in 1900. Although most chemical engineering departments are now in the college of engineering, some chemical engineering departments retain their formal affiliation with chemistry. The situation is similar in computer science, in which some departments are in the college of science and some are in the

college of engineering. The first industrial engineering curriculum was started in 1908 at Pennsylvania State College, and aeronautical engineering was started at the University of Michigan in 1914.^[14] Initially, mining engineering was an interdisciplinary combination of civil and mechanical engineering, electrical engineering was an interdisciplinary combination of mechanical engineering and physics, chemical engineering was an interdisciplinary combination of mechanical engineering and chemistry, and industrial engineering was a combination of engineering and management.

Engineers have long had interest in and disagreements on how engineering should be taught. Laboratory instruction in engineering was started at Stevens Institute of Technology in 1871 and summer camps were started at the University of Michigan in 1874. In the late 1800s mechanical engineers disagreed over whether education should be practical or theoretical—a disagreement that continues. Shop classes (very hands-on!) were considerably more common than laboratory courses at this time. Cooperative education (alternating periods of work and study) is arguably the most important development in higher education that was clearly first developed in engineering. Co-op was started by Herman Schneider at the University of Cincinnati in 1906. Cooperative group learning was also used in engineering classrooms at least as early as 1907^[14] although the principles were not codified at that time. It is clearly difficult to develop any educational method that is totally new.

Development of a professional society to improve engineering education can be traced to 1876 when a joint committee of the American Institute of Mining Engineers and the American Society of Civil Engineers met.^[14] A later joint committee meeting in 1882 included the American Society of Mechanical Engineers. In 1893 the Society for the Promotion of Engineering Education (SPEE) was born at the Chicago World’s Columbian Exposition. At the first meeting of the society in 1894 President DeVolson Wood noted that SPEE was open to both men and women. Unlike the earlier attempts, SPEE survived and became the American Society for Engineering Education (ASEE) in 1946. Engineering has the proud distinction of being the first profession to form a society devoted to professional education.^[14]

From the beginning SPEE published a *Proceedings* that included papers and board minutes. In 1910 a regular *Bulletin* was started that became *Engineering Education* in 1916. When the number of conference papers became too large for the journal, ASEE started the *Annual Conference Proceedings*. The *Proceedings* themselves became very large and filled two or three large volumes every meeting. The 1996 and later *Proceedings* are available on CDs at the ASEE Web site.^[17] The Frontiers in Education (FIE) Conferences were started in 1971 by the Education Group of IEEE, and in 1973 the Engineering Research and Methods (ERM) Division of ASEE started co-sponsoring the FIE conference.^[18] The 1995 and

later *Proceedings of the Frontiers in Education Conferences* are available electronically from the FIE Clearinghouse.^[19] For many years *Engineering Education* tried to fulfill the roles of a society newsletter, a semi-popular magazine, and a learned journal. These multiple roles became increasingly strained and in 1991 publication of *Engineering Education* temporarily ceased and the new magazine *ASEE Prism* was born. In 1993 the *Journal of Engineering Education (JEE)* was restarted. *JEE* has had three editors (Ed Ernst, John Prados, and Jack Lohmann) since being restarted and has successively become more rigorous.

The training of engineering professors in pedagogy was an early and continuing interest of SPEE and ASEE.^[14] In 1901 SPEE called for teaching engineering professors how to teach. Formal training in teaching occurred at the SPEE summer schools from 1911 to 1915 and again from 1927 to 1933. Unfortunately, the dislocations caused by war and depression ended these pioneering efforts. A large number of additional summer schools, most for specific disciplines, have been sponsored since then. The Hammond Report in 1944 reiterated the need for systematic development of teaching skills. In 1955 the Grinter Report stated “it is essential that those selected to teach be trained properly for this function.” In 1955 the Interim Committee for Young Engineering Teachers proposed a summer school for new faculty. This was first held as a two-day meeting, “Principles of Learning in Engineering Education,” following the 1958 annual conference of ASEE. Regional institutes were started in 1966 and were eventually put under the ERM Division of ASEE. These programs continue including the highly successful ASEE National Effective Teaching Institutes. The 1983 ASEE Quality in Engineering Education project again called for more training of faculty in teaching.

Although relatively small, the Chemical Engineering Division (ChED) of ASEE has been a leader in improving teaching. The Division started publishing its journal *Chemical Engineering Education (CEE)* in 1966. *CEE* is widely admired as probably the best of the disciplinary journals in engineering education. The mission of *CEE* is to aid in the education of chemical engineers, which is much broader than the current research mission of *JEE*. The Division has sponsored 14 summer schools approximately every five years. The ChED summer schools focus mainly on how to teach new material, and it was not until 1987 that the first how-to-teach workshop was included. Following the success of that workshop, regularly scheduled how-to-teach workshops have been held at every ChED summer school since then and are now required of new faculty, whose travel expenses are partially supported by the summer school.

An engineering course to train ChE teaching assistants how-to-teach was first developed by Jim Stice at the University of Texas, who also developed an in-house teaching workshop for new faculty.^[20] The first course for Ph.D. students in engineer-

Engineering has the proud distinction of being the first profession to form a society devoted to professional education.

ing who planned on academic careers was taught at Purdue University.^[21] Since that time a large number of additional faculty workshops^[22] and regular courses^[23] to improve the teaching of engineering have been developed, and a textbook was published.^[24]

WHY EDUCATION IN PEDAGOGY NOW?

Most engineering professors do not have training in pedagogy. Instead, most are superbly trained in how to do research. If the system isn't broken, why fix it? Unfortunately, with respect to education, the system is broken. When professors learn through on-the-job-training (OJT), the first few classes suffer even if the professors eventually become excellent teachers. Since OJT does not provide a theoretical framework, it is difficult for these professors to understand educational research or to adopt new teaching methods. With the current system some professors never become good teachers. Low retention rates^[25] are partially caused by the current system.

After more than 100 years of calls to improve engineering education, why would anyone believe that a lasting reform can happen now? As the NAE reports^[3, 4] note, the world has changed. Engineering students have changed; they are much more diverse including gender, ethnicity, age, part-time status, and educational background than they used to be. The increase in diversity is welcomed, but most of the students are weaker in mathematics, particularly algebra, than they used to be.^[26] In addition, the average work ethic appears to be lower.^[26] Different active-learning teaching methods are needed and fortunately are available.^[24, 27, 28] New technical content such as nano-scale engineering, bioengineering, and particulate processing, as well as increased professional content^[9] such as teamwork, ethics, work experience, and global/societal effects, all need to be included. Employers are expecting more of graduates.^[3, 27]

If more content and different teaching methods are expected, what do we do less of?

Students know that they may need more than four years to earn a degree. Faculty will need to reduce the time spent lecturing to provide time for more effective active learning methods.^[24, 27, 28]

Faculty need to replace hand calculations with computer methods and to remove other obsolete material such as Ponchon-Savarit diagrams.^[29] Unfortunately, there is never agreement on what material to remove, which makes all suggestions for removal of material controversial. Although this will not

be a popular suggestion, I also think that we need to reduce the amount of theory and analysis. Schools need to experiment with unified and spiral curricula^[30] as well as with curricula with a smaller required core and more options.

The good news is we know how to teach professors how to improve their teaching, and it is not that difficult or expensive. Both teaching workshops^[20, 22, 31, 32] and regular for-credit courses^[21, 23] are effective in increasing the teaching competence of attendees. The bad news is we don't do this routinely and professors who have been in academe for a period of time have difficulty finding the motivation and time to attend workshops. Stice^[20] found that experienced professors will attend summer teaching workshops if they are paid to attend. Our experience at Purdue is similar. New professors on the other hand (including those returning to

Teaching senior Ph.D. students how-to-teach has the advantages that they are used to taking courses, they have time, and knowing how to teach instead of learning on the job provides them significantly more time to start their research programs when they become assistant professors.

academe from industry), are much more interested in learning how-to-teach. Teaching senior Ph.D. students how-to-teach has the advantages that they are used to taking courses, they have time, and knowing how to teach instead of learning on the job provides them significantly more time to start their research programs when they become assistant professors.^[23] Courses on how-to-teach also provide access to modern engineering education scholarship by providing a vocabulary and introducing engineering professors to theories of development and learning. If the vast majority of engineering professors are not taught the basics of pedagogy, then the researchers in engineering education will end up talking to themselves and there will be very little if any impact of the research on the teaching of engineering.

SCHOLARSHIP IN ENGINEERING EDUCATION

Early scholarship in engineering education did not have to be very rigorous to be accepted. Many papers were basically "I tried this new method and the students loved it," and were published with little or no data and often few references. After restarting in 1993, *JEE* was still not very rigorous compared to journals in education and educational psychology, but it was generally more rigorous than the proceedings published

by ASEE and than other engineering education journals. The new higher standards encouraged including student course evaluations and/or surveys plus appropriate references. This is a quality level that all engineering professors can meet if they are pushed to do so. I will call this level the old paradigm for quality in engineering education research. Note that during this period engineering was typical of many other disciplines—disciplinary educational research was not held to a very high standard.

The watershed event in educational research occurred in 1990 with the publication of Ernest Boyer's *Scholarship Reconsidered*.^[33] Boyer defined four scholarships:

1. *Discovery, which in engineering is the usual high-prestige technical research.*
2. *Application, which in engineering is applied research and is relatively high prestige.*
3. *Integration, which includes interdisciplinary research and writing scholarly books, is the search for meaning and significance in research. Unfortunately, most university faculty have yet to recognize the importance of the scholarship of integration in engineering education.*^[34]
4. *Teaching, which was quickly extended to a scholarship of teaching and learning, is scholarly study to improve teaching and learning, not teaching itself. Unlike researchers in the other scholarships, however, scholars of teaching and learning must be good teachers or they will lose credibility.*

Boyer's book had an enormous impact on the scholarship of teaching and learning. A few universities started accepting the scholarship of teaching and learning almost overnight, but most universities took significantly longer.^[34] And engineering was not an earlier adopter.^[35]

There were a variety of other factors influencing engineering education research at the end of the 20th century and the beginning of the 21st century. First, and most important, money talks. When NSF started providing funds for engineering education research it made that research affordable and more prestigious. Additionally, the requirement for a teaching component in NSF CAREER proposals forced most new faculty to think more seriously about teaching and educational research. And, the requirement for broad impact statements in regular technical proposals probably had a positive effect despite a backlash from many researchers.

Second, ABET requirements forced many professors to be more serious about outcomes and to pay attention to assessment. ABET clearly had a positive impact despite push back from professors who disliked ABET's methods. Third, the NAE charted CASEE and started to consider educational accomplishments in admission to NAE. CASEE probably had more impact since NAE admission affects only a small fraction of professors. Fourth, the general interest in good college teaching from government, parents, students, and college

presidents impacts engineering deans, department heads, and professors. Fifth, with more research support and more rigorous judging of quality, some schools now include engineering education research grants and papers in their promotion and tenure decisions, although they may still be undervalued compared to technical research. Sixth, as the faculty environment became even more pressurized, new faculty—who were expected to “hit the ground running”—found that receiving training in how-to-teach as Ph.D. students helped them have more time for research during the first few years.^[23]

The final important factor influencing engineering education research was the gradual development of *JEE* as a rigorous research journal. As noted previously, using the old paradigm the threshold standard in *JEE* was to include student course evaluations and/or surveys plus appropriate references. This level was a bit higher than many other engineering education journals, but still not up to world-class standards as set by the best journals in education and educational psychology. In 2003 *JEE* moved its acceptance standards for research papers to a level of rigor on par with highly ranked education journals.^[1] The rigor required to publish research papers in *JEE* outstrips the rigor of the average research paper published in other engineering education journals and in conference proceedings. Because of this *JEE* has had a positive effect on the quality of research published in these other venues.

The changes in *JEE* have resulted in unexpected consequences. First, professors not trained in educational research have found that the research articles in the journal are a lot more difficult and less fun to read. Unfortunately, if the average engineering professor does not read *JEE* or other engineering education journals, engineering education research will probably have little impact in the classroom. Second, most engineering professors need to collaborate with someone with the right skill set to reach the quality level required. This partially caused the third effect, an acceptance rate that plummeted to about 10 %. The other cause for the low acceptance rate is that as a new discipline, engineering education has a low consensus on the standards required for scholarship, which is known to reduce journal acceptance rates.^[36] Unfortunately, with a 10 % acceptance rate many prospective authors will not submit to *JEE*, preferring to publish elsewhere. It is now significantly harder for most ChE professors to publish in *JEE* than in the most prestigious ChE journals. Fourth, the change in rigor increased the amount of collaborative research published in *JEE*. A fifth effect was that the total number of papers has decreased in the last five years, but the number of review papers appeared to increase. Apparently, engineering faculty can write critical reviews even if they are not trained in rigorous educational research methods.

Finally, there are many topics of interest to engineering professors that cannot be published in *JEE* because they are not research topics. Examples are articles on meeting ABET assessment requirements, curriculum developments, how to

teach a particular topic, and course development. Fortunately, chemical engineers can publish on these topics in *CEE*, which is a refereed journal that does not focus totally on research. For professors in most other engineering disciplines, ASEE discovered that there was a large publishing hole between the semi-popular *Prism* magazine and the rigorous research published in *JEE*. To fill this hole ASEE started the applications-oriented electronic journal *Advances in Engineering Education* in 2007.^[37]

Scientifically rigorous research in engineering education meets a series of well-known criteria.^[1, 27, 36, 38] Rigorous educational research needs to be planned in advance—trying a new method in class, finding it seemed to work, and then deciding to write an article is not rigorous research although it may be valuable to other professors. Rigorous educational research requires stating hypotheses on significant questions in advance and then testing them during the research.

A thorough literature review is required. The research should be grounded with a theory of learning or human development. The research tools will consist of quantitative (statistical) methods; qualitative methods such as survey instruments, protocol analysis, ethnography, and interview techniques; or mixed methods. Methods should be selected that allow direct investigation of the hypotheses. Before conducting the research, approval or an exemption must be obtained from the Institutional Review Board (IRB) if students are involved. Finally, the research will be presented to peers through oral and/or written papers. These requirements set the level for the new paradigm of quality in engineering education research.

The Engineering Education Research Colloquies^[7] developed a national agenda for research in engineering education.^[8] The five research areas are^[8]:

- “**Area 1-Engineering Epistemologies:** Research on what constitutes engineering thinking and knowledge within social contexts now and into the future.”
- “**Area 2-Engineering Learning Mechanisms:** Research on engineering learners’ developing knowledge and competencies in context.”
- “**Area 3-Engineering Learning Systems:** Research on the instructional culture, institutional infrastructure, and epistemology of engineering educators.”
- “**Area 4-Engineering Diversity and Inclusiveness:** Research on how diverse human talents contribute solutions to the social and global challenges and relevance of our profession.”
- “**Area 5-Engineering Assessment:** Research on, and the development of, assessment methods, instruments, and metrics to inform engineering education practice and learning.”

Although quite broad in scope, these five areas do not and were not expected to encompass all areas of research of inter-

est. For example, research on the motivations of engineering students and how they differ from the motivations of students in other disciplines is certainly of interest.

The vast majority of engineering professors are unfamiliar with these research areas and with the tools required for rigorous educational research. They are unfamiliar with learning and human development theories and in many cases are unfamiliar with teaching methods other than lecture, lab, and design. Although they may be knowledgeable about statistical methods, educational statistics tend to be different since many variables cannot be controlled and correlation coefficients (r values) of 0.5 are considered high. Qualitative methods are probably unheard of and may not be trusted. Although engineers have started to do assessments for ABET accreditation, these assessments are fairly crude compared to rigorous educational research.

How can an engineering professor get started in engineering education research at the level of rigor of the new paradigm? Perhaps the easiest approach is to find a collaborator from Education who can provide the necessary theories and research tools. By working with an expert, reading about basic pedagogical methods,^[24] taking teaching workshops such as at the ChED Summer School or the ASEE NETI, reading about scientific research methods in education,^[27, 36, 38] attending workshops on rigorous engineering education research,^[39] and studying articles in *JEE* and other journals, engineering professors can slowly pull themselves up to a level where they can compete for NSF grants, do rigorous research, and publish in the highest quality journals.

PH.D. PROGRAMS IN ENGINEERING EDUCATION

Whether their degree is from an engineering education department or a disciplinary department, Colleges of Engineering must ensure that all graduates earning Ph.D. degrees based on research in engineering education do their research at the level of the new paradigm. Thus, they must have some knowledge and skill with both quantitative and qualitative research methods. Graduates who are only trained in the old paradigm have obsolete skills and represent a tragedy for both the graduate and for the nascent discipline of engineering education.

In a very short time (a 2002 paper on the scholarship of teaching and learning in engineering had no mention of Ph.D. programs in engineering education^[35]) three different models have been developed for students who want to earn a Ph.D. doing research in engineering education. The oldest model is to do engineering education research in a disciplinary department.

The Department of Industrial Engineering at the University of Pittsburgh uses this model and produces very well qualified graduates. A scattering of chemical engineering departments have awarded Ph.D. degrees to students who did engineering

education research. An advantage of this model is that since graduates have to take the required disciplinary courses and pass the appropriate qualifying examinations, they are well qualified to teach and collaborate with other professors in their discipline. This model is also inexpensive and easy to implement since it fits within an existing unit. The lack of structure, however, can also mean a lack of quality control. If the members of the Ph.D. research committees are not familiar with rigorous engineering education research, they may set the requirements for rigor too low and not require students to take appropriate research methods courses in education, and the resulting research may be conducted at the level of the old paradigm. These graduates, although perfectly capable in teaching and curriculum development, will not be prepared to do engineering education research at the level of the new paradigm. This danger is much more severe than with disciplinary research because faculty have been trained to do disciplinary research and the level of consensus of what is good scholarship is much higher in technical areas than in engineering education.^[36] To some extent this danger can be alleviated by treating the research as interdisciplinary and having a co-advisor from the College of Education. Unfortunately, I have observed several cases where a recent Ph.D. who did research in engineering education within a disciplinary department was not trained to perform research at the desired level of rigor.

The second model is to develop a new department such as engineering education at Purdue^[10] and Virginia Tech,^[11] engineering and science education at Clemson,^[12] and engineering and technology education at Utah State.^[13] The Purdue Department of Engineering Education (ENE) started its Ph.D. pro-

Purdue ENE Ph.D. Requirements^[41]	
• Admission: B.S. or M.S. in engineering, high GPA, letters, statement of interest.	
– Must have high quality students – not a consolation prize	
• Courses:	
– Grad-level technical engineering courses	15 cr.
<i>May use transfer credit from engineering master's program.</i>	
– ENE Intro course & ENE seminar	4 cr.
– Intro Statistics & Intro Ed Research	6 cr.
– Research Methods electives	6 cr.
– ENE electives and Grad elective	9 cr.
	40 cr.
• Thesis	

Figure 1. Purdue University's ENE Ph.D. requirements.

How can an engineering professor get started in engineering education research at the level of rigor of the new paradigm? Perhaps the easiest approach is to find a collaborator from Education who can provide the necessary theories and research tools.

gram in 2005 and has two graduates (Dr. Tamara Moore who transferred into ENE from Math Education and Dr. Euridice Oware who transferred into ENE from Civil Engineering). The Virginia Tech Department of Engineering Education started its Ph.D. program in 2007. Both of these Ph.D. programs are cross-disciplinary and require course work in ENE, another engineering department, and the College of Education. The Clemson Department of Engineering and Science Education has established a Certificate in Engineering and Science Education for graduate students and plans on starting a graduate degree program. Although the Engineering and Technology Education Department at Utah State University is part of the College of Engineering, its cross-disciplinary Ph.D. is currently granted by the College of Education. The Utah State program focuses on curriculum and instruction mainly for technology education teachers. Utah State is in the process of developing a Ph.D. program in engineering education that would be granted by the College of Engineering. I believe these departments should be within the College of Engineering so that graduates will think of themselves as engineers and will be able to work with other engineering professors. The advantages of developing a separate degree-granting department include the higher prestige of departments, the ease in tapping sources for research and development money, and the greater stability of departments. The main disadvantage is the cost of developing a new administrative structure.

The third model is to develop an interdisciplinary program in engineering education at the Ph.D. level. There are, of course, an almost infinite variety of ways this could be done. For example, plans at Washington State University are that students will receive their degree from their engineering department (*e.g.*, ChE) and will meet additional requirements of the interdisciplinary program hosted by the Engineering Education Research Center.^[40] These requirements will probably include taking courses from the College of Education and engineering education courses.

What courses are typically included in a Ph.D. program in engineering education? The requirements for Purdue's program,^[41] listed in Figure 1, are fairly typical. The research methods courses either from the College of Education or from ENE are critically important regardless of the model selected. In addition, research advisors must ensure that research is rigorous. One of the electives in ENE that is highly recommended is a how-to-teach course.^[23] Most engineering colleges at universities with a College of Education could offer an interdisciplinary program similar to Figure 1 with the development of a few specialized courses. The model used for administering the program is less important than

the availability of required courses and of interested research advisors who are knowledgeable in engineering and in educational research.

The new programs in engineering education may also help engineering address one of the problems left over from its military heritage—a culture that keeps the number of women studying and teaching engineering low. Women have been attracted to the Ph.D. programs in engineering education and to the faculty in the engineering education departments. For example, 16 of the 28 graduate students in Purdue's School of Engineering Education are female (57 %) and 7 of the 18 faculty members are female (39 %).

CAREERS FOR GRADUATES IN ENGINEERING EDUCATION

After formation of engineering education departments, we were continually asked “What will the graduates do?” We believe there will be significant opportunities for graduates of the Ph.D. programs. If current departments expand or new engineering education departments are formed, new graduates will be in demand for tenure-track positions in these departments. We also think that graduates will be attractive candidates for both tenure-track and instructor positions in first-year engineering programs, at undergraduate institutions, and at community colleges. Some large disciplinary departments at research universities will also be interested in hiring graduates, particularly those that have a disciplinary Ph.D., as an educational expert. In addition, graduates are likely to be attractive candidates for non-tenure-track positions at teaching centers, as the educational leader in engineering research centers, and in engineering outreach to K-12. For at least the next 10 years demand will probably be greater than the supply of graduates.

For long-term viability of both departments and graduates, universities need to make some modest changes. Promotion and tenure committees will need to learn to accept engineering education research as equivalent to technical research, and they will need to learn to evaluate the quality of engineering education research. In addition, engineering education researchers must do research that eventually commands the respect of engineering faculty who do technical research.

What careers will be open for students who earn master's degrees in engineering education? Both Virginia Tech^[11] and Utah State^[13] have master's programs. Based on feedback from Purdue's industrial advisory council, we believe that there is a large, untapped market for graduates with engineering education master's degrees in the training programs

of large companies. If they have industrial experience, these graduates are also expected to find professorial positions at community colleges. Staff positions at four-year colleges and research universities in first-year engineering programs, technology programs, instructors for lower-division courses, and outreach programs are also likely to hire graduates. Again, the demand will probably be greater than the supply for quite some time.

CONCLUSIONS

Engineering education requires a change in the status quo in which new professors receive no training in how to teach. If the attendees are motivated to learn, teaching Ph.D. students and new professors to improve their teaching is neither difficult nor expensive. To continually improve engineering education we also need to have professors who conduct rigorous engineering education research. To improve the quality of engineering education research, professors must transform their approach to a new, scientifically rigorous paradigm. This new paradigm requires that engineering education researchers plan in advance, do a thorough literature review, state and test hypotheses, use appropriate quantitative and qualitative research tools, and disseminate results to peers. An increasing number of students are doing their Ph.D. research on engineering education. Regardless of the type of program, it is vitally necessary that graduate students conduct their research at the level of the new engineering education research paradigm.

ACKNOWLEDGMENT

This paper is based on a presentation at Washington State University, July 27, 2007.

REFERENCES

- Lohmann, J.R., "The Editor's Page," *J. Eng. Educ.*, **92** (1), 1 (2003)
- Lohmann, J.R., "Editor's Page: Refining our Focus," *J. Eng. Educ.*, **97** (1), 1 (2008)
- NAE Committee on the Engineer of 2020, *The Engineer of 2020*, National Academies Press, Washington, DC (2004)
- NAE Committee on the Engineer of 2020 Phase II, *Educating The Engineer of 2020*, National Academies Press, Washington, DC (2005)
- <<http://www.nae.edu/nae/caseecomnew.nsf?OpenDatabase>> Accessed March 19, 2008
- <<http://www.areonline.org/>> Accessed March 19, 2008
- Steering Committee National Engineering Education Research Colloquies, "The National Engineering Education Research Colloquies," *J. Eng. Educ.*, **95** (4), 257 (2006)
- Steering Committee National Engineering Education Research Colloquies, "The Research Agenda for the New Discipline of Engineering Education," *J. Eng. Educ.*, **95** (4), 259 (2006)
- <<http://www.abet.org/>> Accessed March 19, 2008
- <<https://engineering.purdue.edu/ENE/>> Accessed March 19, 2008
- <<http://www.eng.vt.edu/main/index.php>> Accessed March 19, 2008
- <<http://www.clemson.edu/ese/>> Accessed March 19, 2008
- <<http://www.neng.usu.edu/ete/>> Accessed March 19, 2008
- Grayson, L.P., *The Making of an Engineer*, Wiley, New York (1993)
- Lucas, C.J., *American Higher Education. A History*, St. Martin's Griffin, New York (1994)
- Westwater, J.W., "The Beginnings of Chemical Engineering Education in the United States," in Furter, W.F. (Ed.), *History of Chemical Engineering*, Washington, D.C., American Chemical Society, Advances in Chemistry Series, **190**, 140-152 (1980)
- <<http://www.asee.org/>> Accessed March 22, 2008
- Biedenbach, J.M., and L.P. Grayson, "Foreward," *Proceedings Third Annual Frontiers in Education Conference*, p. viii, IEEE, New York (1973)
- <<http://fie.engrng.pitt.edu/>> Accessed March 22, 2008
- Stice, J.E., "A Model for Teaching New Teachers How to Teach," *Eng. Educ.*, **75** (2), 83 (Nov. 1984)
- Wankat, P.C., and F.S. Oreovicz, "Teaching Prospective Faculty Members About Teaching: A Graduate Engineering Course," *Eng. Educ.*, **75** (2), 84 (Nov. 1984)
- Brawner, C.E., R.M. Felder, R. Allen, and R. Brent, "A Survey of Faculty Teaching Practices and Involvement in Faculty Development Activities," *J. Eng. Educ.*, **91**, 393 (2002)
- Wankat, P.C., and F.S. Oreovicz, "Teaching Prospective Engineering Faculty How To Teach," *Intl. J. Eng. Educ.*, **21** (5) 925 (2005)
- Wankat, P.C., and F.S. Oreovicz, *Teaching Engineering*, McGraw-Hill, NY (1993) <<https://engineering.purdue.edu/ChE/AboutUs/Publications/TeachingEng/index.html>>
- Seymour, E., and N.M. Hewitt, *Talking About Leaving: Why Undergraduates Leave the Sciences*, Westview, Boulder, CO (1997)
- Brannan, K.P., and P.C. Wankat, "Survey of First-Year Programs," *Proceedings ASEE 2005 Annual Conference*, Portland, OR (June, 2005). CD, session 1353
- Heywood, J., *Engineering Education : Research and Development in Curriculum and Instruction*, IEEE Press/Wiley, Hoboken, NJ (2005)
- Prince, M., "Does Active Learning Work? A Review of the Research," *J. Eng. Educ.*, **93**, 223 (2004)
- Wankat, P.C., "What Will We Remove From the Curriculum to Make Room for X? Bite the Bullet—Throw Out Obsolete Material," *Chem. Eng. Educ.*, **21** (2), 72 (Spring 1987)
- DiBasio, D., L. Comparini, A.G. Dixon, and W.M. Clark, "A Project-Based Spiral Curriculum for Introductory Courses in ChE. Part 3. Evaluation," *Chem. Eng. Educ.*, **35** (2), 140 (Spring 2001)
- Conley, C.H., S.J. Ressler, T.A. Lenox, and J.A. Samples, "Teaching Teachers to Teach Engineering—T4E," *J. Eng. Educ.*, **89**, 31 (2000)
- Kennedy, D., *Academic Duty*, p. 75, Harvard Univ. Press, Cambridge, MA (1997)
- Boyer, E., *Scholarship Reconsidered: Priorities of the Professoriate*, Carnegie Foundation for the Advancement of Teaching, San Francisco, Jossey-Bass (1990)
- Radcliffe, D.R., "Shaping the Discipline of Engineering Education," *J. Eng. Educ.*, **95** (4), 263 (2006)
- Wankat, P.C., R.M. Felder, K.A. Smith, and F.S. Oreovicz, "The Engineering Approach to the Scholarship of Teaching and Learning," in M. T. Huber and S. Morreale (Eds.) *Disciplinary Styles in the Scholarship of Teaching and Learning: Exploring Common Ground*, American Association for Higher Education, Washington, D.C., 217-237 (2002). <<http://www.ncsu.edu/felder-public/papers/Scholarshipchapter.pdf>>
- Borrego, M., "Conceptual Difficulties Experienced by Trained Engineers Learning Educational Research Methods," *J. Eng. Educ.*, **96** (2), 91 (2007)
- <<http://advances.asee.org/>> Accessed March 19, 2008
- Shavelson, R.J., and L. Towne, *Scientific Research in Education*, National Academy Press, Washington, D.C. (2002)
- Streveler, R.A., and K.A. Smith, "Conducting Rigorous Research in Engineering Education," *J. Eng. Educ.*, **95** (2) 103 (2006)
- Professor Denny Davis, private communication, July 27, 2007
- <<https://engineering.purdue.edu/ENE/Academics/Graduate/Doctorate/requirements>> Accessed March 19, 2008 □

QUICK AND EASY RATE EQUATIONS FOR MULTISTEP REACTIONS

PHILLIP E. SAVAGE

University of Michigan • Ann Arbor, MI 48109-2136

In many different aspects of chemical engineering education, we teach students first to analyze a general system and then to simplify that general analysis as allowed by the specific system being examined. For example, we show students the general energy balance and then subsequently show how it can be simplified when applied to special cases (e.g., adiabatic systems, steady state systems, systems with negligible changes in kinetic or potential energy). We show students the equations of motion in fluid mechanics and then subsequently show how they can be simplified for special cases (e.g., steady flow, incompressible fluids, Newtonian fluids). In the field of chemical kinetics, an opportunity exists to apply this same educational approach when teaching students how to develop reaction rate equations based upon application of the quasi-stationary-state approximation (QSSA) to the governing chemical mechanism. The purpose of this article is to make this opportunity more widely known.

Chemical kinetics and reaction engineering textbooks^[1-5] discuss techniques for deriving closed-form analytical rate equations from sets of elementary reaction steps. Types of reaction systems covered include chain reactions, catalysis, and chemical vapor deposition. The QSSA is one of the tools discussed in texts. This approximation, which in many texts gets the confusing and potentially misleading label of “steady-state”^{*} attached to it, allows one to neglect the comparatively small net reaction rate for a reactive intermediate (RI) relative to its very fast formation and disappearance rates. The result is that one can take the formation and disappearance rates to be approximately equal, and then solve algebraically for the concentration of the reactive intermediate.

$$\underbrace{r_{\text{net,RI}}}_{\text{very small}} = \underbrace{r_{\text{formation,RI}}}_{\text{large}} - \underbrace{r_{\text{disappearance,RI}}}_{\text{large}} \approx 0 \quad (1)$$

Oftentimes, this result contains the concentration(s) of other

reactive intermediates, so the QSSA must be applied next to those reactive intermediates. This procedure is repeated to get explicit expressions for each reactive intermediate.

The application of the QSSA in textbooks almost always involves only one or two reactive intermediates, because the number of simultaneous equations and tediousness of the algebra, if done manually, grow as the number of reactive intermediates increases. Most texts, when covering multistep reactions with two or more intermediates, teach students to make restrictive assumptions (e.g., rate determining steps), which simplify the algebra. The price paid for the simplified mathematics, though, is a less general rate equation. If there is a shift in the rate-determining step with temperature or conversion, for example, the rate equation will no longer apply.

The lack of coverage of QSSA applications to larger multistep reaction systems in chemical engineering education need not persist. Easy-to-use general methods exist to develop analytical rate equations for arbitrarily large multistep reactions without making assumptions about the existence or identities of rate-determining steps. This article describes these general methods. One method, developed by Helfferich,^[6-8] applies to

Phillip Savage is a professor of chemical engineering at the University of Michigan. He received his B.S. from Penn State in 1982 and his M.Ch.E. (1983) and Ph.D. (1986) degrees from the University of Delaware, all in chemical engineering. His research and teaching interests focus on the rates, mechanisms, and engineering of organic chemical reactions. Current research projects deal with renewable energy from biomass and environmentally benign chemical synthesis.



* The QSSA has nothing to do with steady states, either mathematically or conceptually. The QSSA deals with process rates (rates of chemical reactions), and not rates of change (dC/dt). This approximation does not require or imply that $dC_{\text{RI}}/dt = 0$ nor does it require or imply that C_{RI} is constant. That using the term “steady state” creates confusion is evident in textbooks and educational articles where authors erroneously state that this approximation means the concentration of the reactive intermediate (RI) is constant!

reactions wherein all reactant, final product, and free catalyst concentrations are much greater than the concentrations of the intermediates. A second method, based upon work published by Christiansen,^[9,11] relaxes the requirement that the catalyst concentration exceed that of the reactive intermediates.

APPLICABILITY

The formulas given in this article provide the rate equation for any multistep chemical reaction mechanism that meets the following criteria.

- The steps in the mechanism are all sequential (no branches).
- None of the steps involve more than one molecule of reactive intermediate as reactant or more than one molecule of reactive intermediate as product (so the set of algebraic equations from application of the QSSA can be solved using linear algebra).
- All of the intermediates are present only in trace-level quantities (so the QSSA can be applied to each).

Networks that meet these three criteria are said to be “simple.”

Many reactions catalyzed by acid, base, organometallic complexes, or solid surfaces meet these criteria. The catalytic cycle in Figure 1,^[12] which accounts for the synthesis of bisphenol A from acetone and phenol, is one example.

NOTATION

We adopt the notation used in the original literature. X_i designates reactive intermediates, which by definition are present in trace level. The reaction steps are written with the reactive intermediates (X_i) appearing as the explicit reactant and product in a step. Any co-reactant (or co-product) molecules in a step appear either above (or below) the arrow for that reaction step. We use a double subscript notation for the rate coefficients. The first subscript identifies the reactive intermediate involved as a reactant in that step and the second subscript identifies the reactive intermediate that is formed.

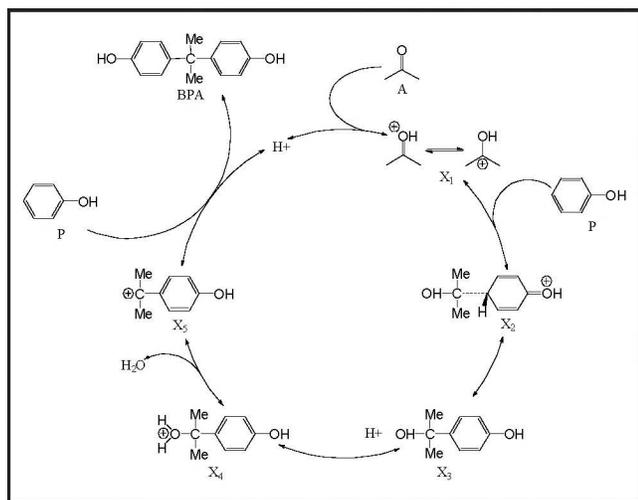


Figure 1. Catalytic cycle for BPA synthesis from phenol and acetone (adapted from Ref [12]).

To illustrate this notation, consider the reaction $X_i + B \rightleftharpoons X_j$. The forward rate constant is k_{ij} and the reverse rate constant is k_{ji} . We rewrite this step as $X_i \xrightleftharpoons{B} X_j$, with B appearing above the arrow because it is a co-reactant. The pseudo-first-order forward rate coefficient for this step is λ_{ij} , where $\lambda_{ij} = k_{ij}C_B$. The pseudo-first-order reverse rate coefficient is λ_{ji} , where $\lambda_{ji} = k_{ji}$. The net rate of this reversible reaction step would be written as

$$-r_B = k_{ij}C_{X_i}C_B - k_{ji}C_{X_j} = \lambda_{ij}C_{X_i} - \lambda_{ji}C_{X_j} \quad (2)$$

Using pseudo-first-order rate coefficients (λ_{ij}) allows all rates to be written explicitly in terms of the concentrations of the reactive intermediates and the reactant and product.

RATE EQUATION – HELFFERICH METHOD (BULK CATALYSIS)

Helfferich developed this first method while doing process development work for Shell Chemical. It was homogeneous reactions of commercial significance catalyzed by transition metals that provided motivation. In these systems, the free catalyst concentration was large relative to the concentrations of the catalyst-containing reactive intermediates. The rate equation for such a simple multistep network, which converts reactant A into end product P, is^[6-8]

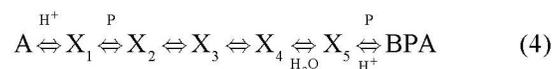
$$r_p = \frac{\prod_{i=0}^{k-1} \lambda_{i,i+1} C_A - \prod_{i=0}^{k-1} \lambda_{i+1,i} C_P}{\sum_{i=1}^k \left(\prod_{l=1}^{i-1} \lambda_{l,l-1} \prod_{l=i}^{k-1} \lambda_{l,l+1} \right)} \quad (3)$$

where r_p is the rate of forming product P, $\prod_{i=0}^{k-1} \lambda_{i,i+1}$ is the product of all of the forward pseudo-first-order rate coefficients, $\prod_{i=0}^{k-1} \lambda_{i+1,i}$

is the product of all of the reverse pseudo-first-order rate coefficients in the multistep reaction, and the index k is the number of steps in the sequence. If the lower limit in the product exceeds the upper, the product is taken to be equal to unity. The denominator in the rate equation involves a summation over a double product. Refer to Helfferich^[6,7] for a simple, easy-to-remember way to perform these operations and generate the denominator without going through the formalism of evaluating each term in the summation.

Application

Figure 1 shows the multistep reaction for the acid-catalyzed synthesis of bisphenol A from acetone (A) and phenol (P). This six-step mechanism can be written as



Acetone is species number zero and BPA is species number six. For this network the relationships between the pseudo-first-order rate coefficients and the true rate constants are

$$\begin{aligned}
\lambda_{01} &= k_{01} C_{H^+} & \lambda_{10} &= k_{10} \\
\lambda_{12} &= k_{12} C_P & \lambda_{21} &= k_{21} \\
\lambda_{23} &= k_{23} & \lambda_{32} &= k_{32} \\
\lambda_{34} &= k_{34} & \lambda_{43} &= k_{43} \\
\lambda_{45} &= k_{45} & \lambda_{54} &= k_{54} C_{H_2O} \\
\lambda_{56} &= k_{56} C_P & \lambda_{65} &= k_{65} C_{H^+} \quad (5)
\end{aligned}$$

By applying the formula for the rate equation to this specific example

$$r_{BPA} = \frac{\prod_{i=0}^5 \lambda_{i,i+1} C_A - \prod_{i=0}^5 \lambda_{i+1,i} C_{BPA}}{\sum_{i=1}^6 \left(\prod_{l=1}^{i-1} \lambda_{l,l-1} \prod_{l=i}^5 \lambda_{l,l+1} \right)} \quad (6)$$

one can very quickly write the rate as

$$r_{BPA} = \frac{\lambda_{01} \lambda_{12} \lambda_{23} \lambda_{34} \lambda_{45} \lambda_{56} C_A - \lambda_{10} \lambda_{21} \lambda_{32} \lambda_{43} \lambda_{54} \lambda_{65} C_{BPA}}{\lambda_{12} \lambda_{23} \lambda_{34} \lambda_{45} \lambda_{56} + \lambda_{10} \lambda_{23} \lambda_{34} \lambda_{45} \lambda_{56} + \lambda_{10} \lambda_{21} \lambda_{34} \lambda_{45} \lambda_{56} + \lambda_{10} \lambda_{21} \lambda_{32} \lambda_{45} \lambda_{56} + \lambda_{10} \lambda_{21} \lambda_{32} \lambda_{43} \lambda_{56} + \lambda_{10} \lambda_{21} \lambda_{32} \lambda_{43} \lambda_{54}} \quad (7)$$

Replacing the λ_{ij} in the rate equation with the corresponding k_{ij} and any co-reactant concentration for that step, and then simplifying leads to the general form of this rate equation as

$$r_{BPA} = \frac{k_a C_{H^+} C_P^2 C_A - k_b C_{H^+} C_W C_{BPA}}{k_c C_P^2 + k_d C_P + k_e C_W} \quad (8)$$

where the k_i parameters are collections of rate constants for individual steps. This final form of the general rate equation is not very complicated even though no assumptions were made about any step being rate determining.

Rate equations for this system have been reported^[12] to be irreversible and both first-order in phenol ($r_{BPA} = k C_{H^+} C_A C_P$) and second-order in phenol ($r_{BPA} = k C_{H^+} C_A C_P^2$). These experimental rate equations are simply special cases of the general rate equation above. First-order kinetics arise when the second step is rate-determining and irreversible. Second-order kinetics arise when the final step is rate determining and irreversible. If a step is rate-determining, the pseudo-first-order rate coefficients for that step must be very much smaller than the rate coefficients for all other steps in the sequence. That is $\lambda_{ij, rds} \ll$ all other λ_{ij} . Moreover, if a step is irreversible, $\lambda_{ji} = 0$ for that step.

When the second step, $X_1 \overset{P}{\rightleftharpoons} X_2$, is rate-determining, λ_{12} and λ_{21} are much smaller than all other λ_{ij} , so denominator terms containing either λ_{12} or λ_{21} will be much smaller than denominator terms that do not contain these terms. Therefore, only the denominator terms that omit λ_{12} and λ_{21} need to be retained in the rate equation. It is only the second term in the denominator that survives. Moreover, if any step is irreversible, the second term in the numerator vanishes. The rate equation for this scenario then becomes

$$r_{BPA} = \frac{\lambda_{01} \lambda_{12} \lambda_{23} \lambda_{34} \lambda_{45} \lambda_{56} C_A}{\lambda_{10} \lambda_{23} \lambda_{34} \lambda_{45} \lambda_{56}} = \frac{\lambda_{01} \lambda_{12} C_A}{\lambda_{10}} = \frac{k_{01} k_{12}}{k_{10}} C_{H^+} C_P C_A = k_{12} K_{01} C_{H^+} C_P C_A \quad (9)$$

which is precisely a first-order rate equation, as seen experimentally. K_{01} is the equilibrium constant for the first reaction step.

When the final step, $X_5 \overset{P}{\rightleftharpoons} BPA$, is rate determining, only the denominator terms that omit λ_{56} and λ_{65} need to be retained in the rate equation. Also, as before, the contribution for the reverse reaction in the numerator vanishes when any step is irreversible. The rate equation for this scenario is

$$r_{BPA} = \frac{\lambda_{01} \lambda_{12} \lambda_{23} \lambda_{34} \lambda_{45} \lambda_{56} C_A}{\lambda_{10} \lambda_{21} \lambda_{32} \lambda_{43} \lambda_{54}} = \frac{k_{01} k_{12} k_{23} k_{34} k_{45} k_{56} C_{H^+} C_P^2 C_A}{k_{10} k_{21} k_{32} k_{43} k_{54} C_{H_2O}} = k_{56} K_{01} K_{12} K_{23} K_{34} K_{45} \frac{C_{H^+} C_P^2 C_A}{C_{H_2O}} \quad (10)$$

Here we obtain the rate equation that is second order in phenol, as was seen experimentally.

TABLE 1 Form of QSSA Rate Equation for Specific Three-Step Catalyzed Reactions	
Reaction System	General Rate Equation
Heterogeneous Isomerization	$r = \frac{(k_a C_A - k_b C_B) C_T}{1 + k_c C_A + k_d C_B}$
Enzyme Catalysis	$r = \frac{(k_a C_S - k_b C_P) C_E^O}{1 + k_c C_S + k_d C_P}$
Ozone Decomposition	$r = \frac{(k_a C_{O_3}^2 - k_b C_{O_2}^3) C_T}{k_c C_{O_3} + k_d C_{O_3}^2 + k_e C_{O_2} + k_f C_{O_2}^2 + k_g C_{O_3} C_{O_2}}$

This example shows that multistep reactions of commercial significance can be easily treated with this method to obtain general reaction rate equations. The complexity in the form of the general rate equation is no more than that in Langmuir-Hinshelwood rate equations, which have long been used in heterogeneous catalytic kinetics. Significantly, however, one can recover even simpler rate equations (*e.g.*, power-law) for situations where one step is rate determining or where a step or steps are irreversible. Note that this approach of starting with the general equation and then simplifying it for special limiting cases is fully consistent with the approach many take in chemical engineering education.

Extension to Non-Trace Intermediates

The general Helfferich method applies to simple pathways with all reactants, products, and free catalyst present in much higher concentrations than the intermediates. But, there are some reactions where the concentration of one or more intermediates rises above trace level, perhaps because the intermediate is a molecular product rather than being a reactive intermediate. In these cases, the pathway can be broken at those intermediates, and each of the fragments of the overall network can then be treated using the general method described in this article.^[6]

To illustrate, consider the acid-catalyzed dehydration of cyclohexanol in supercritical water^[13] as shown in Figure 2. This network is nonsimple because one of the intermediates, cyclohexene, is not at trace levels. Its concentration is comparable to that of the reactant cyclohexanol and end product methylcyclopentene. Therefore, one cannot use the general formula to write a single rate equation for the conversion of cyclohexanol to methylcyclopentene. One can break the complete network into two piece-wise simple portions, however, and apply Helfferich mathematics to each portion. These two piece-wise simple portions appear as Figure 3.

Using the general formula, one can write the rate equation for the first sequence, the conversion of cyclohexanol (A) to cyclohexene (B) plus water (W).

$$r_1 = \frac{\lambda_{01}\lambda_{12}C_A - \lambda_{10}\lambda_{21}C_B}{\lambda_{10} + \lambda_{12}} = \frac{k_{01}k_{12}C_A C_W C_{H_3O^+} - k_{10}k_{21}C_W^2 C_{H_3O^+} C_B}{(k_{10} + k_{12})C_W} = \frac{k_{01}k_{12}C_A C_{H_3O^+} - k_{10}k_{21}C_W C_{H_3O^+} C_B}{k_{10} + k_{12}} \quad (11)$$

The rate equation for the second portion is, for the general case of all steps being reversible,

$$r_2 = \frac{\lambda_{23}\lambda_{34}\lambda_{45}C_B - \lambda_{32}\lambda_{43}\lambda_{54}C_C}{\lambda_{34}\lambda_{45} + \lambda_{32}\lambda_{45} + \lambda_{32}\lambda_{43}} \quad (12)$$

Note that cyclohexene is designated as species 2 in the second sequence to maintain consistent species indexes. Methylcyclopentene (C) is species 5. Note too that for this second network, the first step (protonation) is irreversible, so $\lambda_{32} = 0$. The rate equation for the second portion then becomes simply

$$r_2 = \lambda_{23}C_B = k_{23}C_B C_{H_3O^+} \quad (13)$$

Akiya and Savage^[13] modeled the kinetics for this system using the two rate equations above. Doing so led to a model that contained only three parameters to be determined from experimental data; two in the first rate equation and one in the second. A numerical modeling approach based on an explicit accounting for each step would have necessitated the inclusion of nine different parameters. Using the Helfferich formula to develop analytical rate equations has certainly simplified the task of parameter estimation.

The interested reader is directed to Helfferich^[6-8] and the references therein for more information regarding additional extensions of this general method.

RATE EQUATION—CHRISTIANSEN MATHEMATICS (TRACE-LEVEL CATALYSIS)

The material presented thus far, when used for catalyzed reaction systems, applies when the concentration of free catalyst is much higher than concentrations of the intermediates. Examples of this situation include acid or base catalysis and many homogeneous transition metal catalyzed reactions. This section treats trace-level catalysis, where the free catalyst concentration is small, and a significant fraction of the total catalyst amount can be bound with intermediates. Enzyme catalysis and

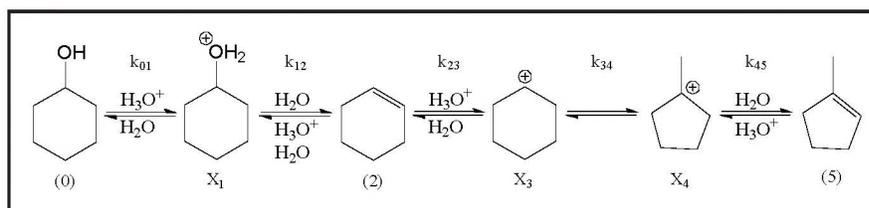


Figure 2. Multistep networks for cyclohexene formation from cyclohexanol (top) and methylcyclopentene formation (bottom) (adapted from Ref. [13])

some heterogeneously catalyzed reaction sequences (e.g., some isomerizations, Eley-Rideal reactions) are examples of simple reaction systems with trace-level catalysis. Christiansen^[9-11] developed the general treatment for systems of this type, Helfferich^[6] discusses it in some detail, and Boudart^[14] provided a short overview nearly 40 years ago.

Helfferich^[6] shows that the rate of conversion of reactant A into product P via the general linear network $\text{cat} \rightleftharpoons X_1 \rightleftharpoons \dots \rightleftharpoons X_{k-1} \rightleftharpoons \text{P}$, is

$$r_p = \frac{\left(\prod_{i=0}^{k-1} \lambda_{i,i+1} - \prod_{i=0}^{k-1} \lambda_{i+1,i} \right) C_T}{D_k^{\text{CH}}} \quad (14)$$

where D_k^{CH} is the Christiansen denominator for a network with k reaction steps. The Christiansen numerator contains C_T , the total catalyst concentration (sum of the concentrations of the free catalyst and all catalyst-containing intermediates). In trace-level catalysis, it is often the total catalyst concentration (amount added to the reactor) that is known. Its distribution among the different catalyst-containing species is not easily measured in engineering applications.

The denominator is the sum of all terms in the Christiansen matrix, and Helfferich describes how to generate these terms.

For a generic 3-step reaction network, $\text{cat}_0 \rightleftharpoons X_1 \rightleftharpoons X_2 \rightleftharpoons \text{cat}_3$, the Christiansen matrix is

$$\begin{vmatrix} \lambda_{12}\lambda_{23} & \lambda_{10}\lambda_{23} & \lambda_{10}\lambda_{21} \\ \lambda_{23}\lambda_{01} & \lambda_{21}\lambda_{01} & \lambda_{21}\lambda_{32} \\ \lambda_{01}\lambda_{12} & \lambda_{32}\lambda_{12} & \lambda_{32}\lambda_{10} \end{vmatrix} \quad (15)$$

An important property of this matrix is that the sum of the terms in each row is proportional to the concentration of one of the catalyst-containing species in the reaction network.^[6] The sum of the terms in the first row is proportional to the

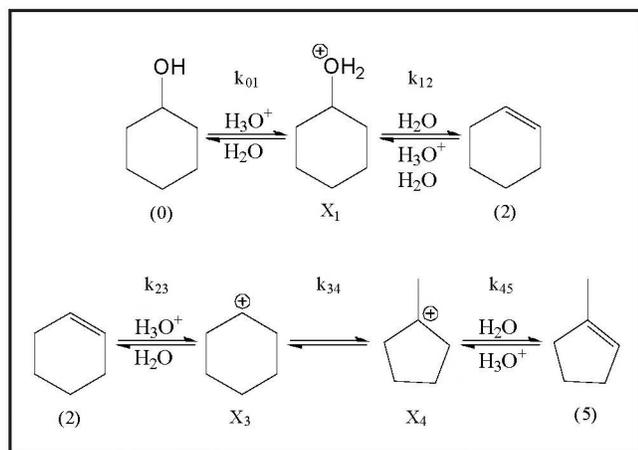
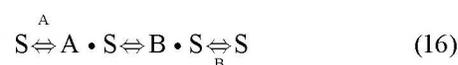


Figure 3. Multistep network for methylcyclopentene formation from cyclohexanol (adapted from Ref. [13])

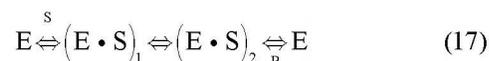
concentration of the free catalyst. The sum of the terms in the second row is proportional to the concentration of intermediate X_1 , and so on. This relationship between the relative abundances of the different catalyst containing species and the relative magnitudes of the sums of the terms in each row allows one to simplify the denominator for cases in which one or more of the catalyst-containing species are present in much higher (or lower) concentrations than the others. For example, if X_2 is the most abundant catalyst species (*macs*), then the sum of the terms in the third row of the matrix will be much larger than the sums of the terms from the other rows. Therefore, one can neglect the small contributions from the other rows, and to a very good approximation the Christiansen denominator can be taken to be the sum of the terms in the third row alone. The number of denominator terms for a network with k steps can therefore be reduced from k^2 to k when there exists a *macs*. Likewise, one can obtain simplification if there exists a *lacs* (least abundant catalyst species). In this case, one can neglect the small contribution made by the sum of the terms in the matrix row corresponding to the reactive intermediate that is the *lacs*.

Application

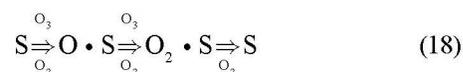
Consider the generic three-step sequence $\text{cat} \rightleftharpoons X_1 \rightleftharpoons X_2 \rightleftharpoons \text{ca}$, which has two catalyst-containing reactive intermediates. Any number of co-reactants or co-products can appear in any of the three steps. Numerous catalytic systems have reaction mechanisms of this form. For example, the solid-catalyzed isomerization $A = B$ can occur through a three-step sequence of adsorption of A, isomerization on the surface, and desorption of B from a surface site (S) back into the fluid phase. The reactive intermediates X_1 and X_2 are surface bound A ($A \cdot S$) and B ($B \cdot S$) respectively.



Some enzyme-catalyzed reactions that convert a substrate, S, into a product, P, proceed through two different enzyme-substrate complexes ($E \cdot S$).^[5] Each complex is a catalyst-containing reactive intermediate.



The heterogeneously catalyzed decomposition of ozone over MnO_2 is another example of a specific reaction that has the same structure as the network under consideration.^[15, 16]



The acid-catalyzed isomerization of cyclohexene (C) to methylcyclopentene (M),^[13] which was examined previously, is one more example.

The general form of the Christiansen rate equation for a

single catalytic cycle with three steps is

$$r = \frac{(\lambda_{01}\lambda_{12}\lambda_{23} - \lambda_{10}\lambda_{21}\lambda_{32})C_T}{\lambda_{12}\lambda_{23} + \lambda_{10}\lambda_{23} + \lambda_{10}\lambda_{21} + \lambda_{23}\lambda_{01} + \lambda_{21}\lambda_{01} + \lambda_{21}\lambda_{32} + \lambda_{01}\lambda_{12} + \lambda_{32}\lambda_{12} + \lambda_{32}\lambda_{10}} \quad (19)$$

To derive this rate equation manually would require algebraic manipulations with two QSSA expressions (one for each intermediate) and the catalyst balance (since the distribution of catalyst material amongst the different forms is not known). This task is tedious, and a tremendous amount of algebra is required to obtain the simplified form of the rate equation above.

Table 1 (page 213) shows the general rate equation for each of the specific application systems in view. The parameters (k_i) in these rate equations are collections of rate constants for individual steps. Rarely does one need to retain all of the terms in the general rate equation. For example, in heterogeneous catalysis, such as the isomerization example, one often assumes that one of the steps is rate determining and that all others are in quasi-equilibrium. If we assume that step 2, the surface reaction ($A \cdot S \rightleftharpoons B \cdot S$), is rate determining ($\lambda_{12}, \lambda_{21} \ll \text{other } \lambda_{ij}$), then the rate equation becomes

$$r = \frac{(\lambda_{01}\lambda_{12}\lambda_{23} - \lambda_{10}\lambda_{21}\lambda_{32})C_T}{\lambda_{10}\lambda_{23} + \lambda_{23}\lambda_{01} + \lambda_{32}\lambda_{10}} \quad (20)$$

Replacing the pseudo-first-order rate coefficients with the rate constants and species concentrations and then simplifying, leads to

$$r = \frac{k_{12}K_{01}C_T(C_A - C_B/K_e)}{1 + K_{01}C_A + K_{32}C_B} \quad \text{where } K_e = K_{01}K_{12}K_{23} \quad \text{and } K_{ij} = \frac{\lambda_{ij}}{\lambda_{ji}} \quad (21)$$

as the rate equation. This Langmuir-Hinshelwood-Hougen-Watson rate equation shows precisely the same dependence of the rate on the concentrations of A and B as the general rate equation for this system in Table 1. Thus, no simplification in form resulted from assuming the existence of a rate-determining step.

For enzyme-catalyzed reactions, step 3, product formation ($(E \cdot S)_2 \rightleftharpoons_p E$), is often irreversible and rate determining ($\lambda_{32}=0$; $\lambda_{23} \ll \text{other } \lambda_{ij}$). The rate equation for this case is

$$r = \frac{(\lambda_{01}\lambda_{12}\lambda_{23})C_T}{\lambda_{10}\lambda_{21} + \lambda_{21}\lambda_{01} + \lambda_{01}\lambda_{12}} \quad (22)$$

Upon replacing the pseudo-first-order rate coefficients with the appropriate rate constants and concentrations, one obtains the rate equation,

$$r = \frac{\left(\frac{k_{12}k_{23}}{k_{21} + k_{12}} \right) C_E^0 C_S}{\left(\frac{k_{10}k_{21}}{k_{01}(k_{21} + k_{12})} \right) + C_S} = \frac{V_{\max} C_S}{K_m + C_S} \quad (23)$$

which is the familiar Michaelis-Menten result. V_{\max} is the maximum reaction velocity (rate). C_E^0 is the total enzyme concentration.

For ozone decomposition, Oyama and coworkers^[15,16] reported that all three steps are irreversible and that absorbed O atoms are the *lacs*. Thus, all reverse rate coefficients will be zero, and the denominator will omit the terms in the second row of the Christiansen matrix. The resulting rate equation is shown below.

$$r = \frac{\lambda_{01}\lambda_{12}\lambda_{23}C_T}{\lambda_{12}\lambda_{23} + \lambda_{01}\lambda_{12}} = \frac{k_{01}C_{O_3}C_T}{1 + \frac{k_{01}k_{12}}{k_{12}k_{23}}C_{O_3}} \quad (24)$$

This example illustrates the utility of Christiansen mathematics for single catalytic cycles. The general rate equation can be written quickly, and then rate laws for special cases (rate determining steps, irreversible steps, *lacs*, etc.) can be recovered by omitting the terms that are negligible.

CLOSING REMARKS

This article outlines and illustrates methods for quickly getting closed-form analytical rate equations for multistep networks using only the QSSA. These methods were developed at an industrial R&D center to deal with practical kinetics issues in chemical process development. Uncatalyzed reactions and those catalyzed by acid, base, homogeneous transition metal complexes, enzymes, and solid surfaces can all be handled by these methods. The chief constraint is that each step must be unimolecular in reactive intermediate. This constraint reduces the utility of this method for chain reactions that include branching, termination, and initiation steps and for heterogeneous catalysis with bimolecular surface reactions.

Though components of these approaches have been in the literature for decades, these methods do not appear in many popular chemical reaction engineering textbooks. I have been teaching these methods in our core chemical reaction engineering graduate course, a senior/graduate elective class on chemical kinetics, and continuing education courses on reaction kinetics. Graduate students or practicing professionals are probably the proper audience for this material. The students appreciate learning about this approach, which allows them to develop a rate equation very quickly for a general case and then simplify it to recover results for numerous special cases. Simplifying the general equation also reinforces the concepts of rate-determining steps, quasi-equilibrium steps, *macs*, and *lacs*.

A more detailed tutorial on the use and teaching of these methods is available from the author upon request. In addition, Helfferich^[6] provides a detailed treatment and many examples.

REFERENCES

1. Fogler, H.S., *Elements of Chemical Reaction Engineering*, 4th ed., Prentice-Hall, Upper Saddle River, NJ (2006)
2. Masel, R.I., *Chemical Kinetics and Catalysis*, Wiley-Interscience, New York (2001)
3. Davis, M.E., and R.J. Davis, *Fundamentals of Chemical Reaction Engineering*, McGraw-Hill, New York (2003)
4. Schmidt, L.D., *The Engineering of Chemical Reactions*, 2nd ed., Oxford University Press, New York (2005)
5. Roberts, G.W., *Chemical Reactions and Chemical Reactors*, Wiley (2009)
6. Helfferich, F.G., *Kinetics of Multistep Reactions*, 2nd ed., Elsevier, Amsterdam (2004)
7. Helfferich, F.G., *J. Phys. Chem.* **93**, 6676 (1989)
8. Chern, J-M, and F.G. Helfferich, *AIChE J.* **36**, 1200 (1990)
9. Christiansen, J.A.Z., *Physik. Chem. Bodenstein-Festband* **69** (1931)
10. Christiansen, J.A.Z., *Physik. Chem.* **B 28**, 303 (1935)
11. Christiansen, J.A., *Adv. Catal.* **5**, 311 (1953)
12. Gates, B.C., *Catalytic Chemistry*, John Wiley & Sons, New York (1992)
13. Akiya, N., and P.E. Savage, *Ind. Eng. Chem. Res.*, **40**, 1822 (2001)
14. Boudart, M., *Kinetics of Chemical Processes*, Prentice-Hall, Englewood Cliffs, NJ (1968)
15. Li, W., G.V. Gibbs, and S.T. Oyama, *J. Am. Chem. Soc.*, **120**, 9041 (1998)
16. Li, W., and S.T. Oyama, *J. Am. Chem. Soc.*, **120**, 9047 (1998) □

ADVISORS WHO ROCK: AN APPROACH TO ACADEMIC COUNSELING

LISA G. BULLARD

North Carolina State University • Raleigh, NC 27695

Extensive educational research has established that student-faculty interactions have a significant impact on student retention and success. Baker and Siryk^[1] found that first-year students who had one-hour advising sessions not only had significantly higher scores on an adjustment scale, but were also less likely to drop out of college than were students who did not have those sessions. Pascarella and Terenzini^[2] found that students who persisted in their chosen major fields of study had a significantly higher frequency of interaction with faculty than did those who chose to switch or drop out. The widely cited “Talking about Leaving” by Elaine Seymour and Nancy M. Hewitt testifies to the importance of good advising:

Failure to find adequate advice, counseling, or tutorial help was cited as contributing to one-quarter (24.0%) of all switching decisions; it was mentioned as a source of frustration by three-quarters (75.4%) of all switchers (for whom it was the third most common source of complaint) and it was an issue raised by half (52.0%) of all non-switchers, for whom it was the second most commonly cited concern. Among all of the factors contributing to attrition, student difficulties in getting appropriate help is the factor which is most clearly derived from flaws in the institutional structure.^[3]

As the director of Undergraduate Studies of the Chemical and Biomolecular Engineering Department at North Carolina State University, I do a great deal of advising. My route to this position was nontraditional. After completing my Ph.D. in chemical engineering at Carnegie Mellon in 1991, I worked at Eastman Chemical Company in Kingsport, TN for nine

years. During that time, I had positions in process engineering, plant engineering, quality management, business process redesign, and business market management. In 2000 I had the opportunity to return to NC State, my undergraduate alma mater, to assume my present position. Besides advising 216 students myself, I coordinate advising for the entire department and also teach several undergraduate courses, including the sophomore course on material and energy balances, a junior-level professional development seminar, and the capstone senior design course. Like all of my departmental colleagues, I had no training whatsoever in either teaching or advising prior to joining the faculty, but I found that my industrial experience was invaluable in doing both. I share my advising story not as a model that all advisors should follow, but as one example of how an advisor might connect with students. Readers who would like more in-depth background on advising skills and approaches can consult one of several excellent references.^[4-7]



Lisa G. Bullard is a teaching associate professor and director of Undergraduate Studies in the Department of Chemical and Biomolecular Engineering at North Carolina State University. She received her B.S. in chemical engineering from NC State, her Ph.D. in chemical engineering from Carnegie Mellon University, and served in engineering and management positions within Eastman Chemical Co. from 1991-2000.

© Copyright ChE Division of ASEE 2008

MY STYLE OF ADVISING

If you want to know my style of advising, step into my office. It doesn't resemble the stereotypical professor's office—a desk covered with computer printouts, teetering piles of journals, and stacks of lab reports in the corner. It looks like someone's home. There are two bentwood Amish rocking chairs gently inclined toward one another, resting on a warm oriental rug. There is a rustic red and white quilt on the wall above the cabinet. Bookshelves line one long wall, but in addition to holding books, they are filled with photographs, mementos from students, artwork, and collages of graduation pictures from years past. On the bottom shelf is a basket with wooden blocks and a jar with seashells to entertain young children who come with their parents for advising appointments. This is my academic home and a sanctuary for students away from home. More than one student has commented, as we rocked and talked, "I feel like I'm rocking on your front porch."

At our first meeting, students are taken aback by the rocking chairs, unsure as to whether they should sit in them or not. Once I sit down and motion them to do the same, they tentatively sit on the edge of the chair, then ease into the molded seat and nestle back. I can see them almost perceptibly take a deep breath and relax. It's impossible to be uptight when you are rocking in a comfortable chair. When we are sitting side by side in the rocking chairs, I'm on the same level with the students. I'm not sitting behind my desk looking at them across a broad expanse—we're in this thing together. I'm not judging them or telling them the answers—I'm listening. Many times people come looking for answers, when all they really need is someone with whom to talk. The rocking chairs remind me that students come one at a time, and during the time I am talking with a student, he or she is the most important person in the world.

Every student has a story. Sometimes the story spills out at the very first meeting, but in most cases, layers are revealed over time. Often I meet students while they are still in high school. When they arrive at NC State, I am their first advisor. I teach many of them in the intro sophomore course, and by the time they graduate, I have had all of them in one or more of the courses I teach. They all experience the rocking chair at some point. It is a privilege and an honor for me to learn their stories, and in doing so, to become part of each story.

The bulletin board behind the rocking chairs is criss-crossed with red ribbons and covered with layers of letters, cards, baby announcements, photographs, and few a poignant programs from memorial services. It's practically an archeological dig in progress, and it reminds me that although students do graduate (at least, that's the goal!), they never truly leave. Although I have only been at NC State since 2000, I have 772 alumni "children" and friends who are working, changing jobs, requesting recommendations for graduate school, getting

I am especially conscious of my role as a mentor to female students—a model that was not available to me as an undergraduate when there were no female professors in the department. I want these young women to know that they can practice engineering and still have a family and a life outside of their profession.

married, having children, and otherwise going about the task of living their lives as chemical engineers and young adults. With their many success stories in mind, I have started inviting them back to speak to current students about the challenges they have faced.

Scattered on the shelves are photographs of my family and artwork that my daughter has generated over the years. The bulletin board contains some special notes in childish writing, like "GO MOM! I LOVE YOU." I am especially conscious of my role as a mentor to female students—a model that was not available to me as an undergraduate when there were no female professors in the department. I want these young women to know that they can practice engineering and still have a family and a life outside of their profession. As someone who has taken time off to have a child, worked part-time, and chosen assignments that allowed me more flexibility during various times during my career, I can assure students that work and life can be balanced to allow room for success in both.

On the side desk sits a computer—the office's one nod to modern technology. When I'm not sitting in a rocking chair, I'm at the computer keeping a steady stream of e-mails flowing in and out. I've never been able to follow the advice of efficiency experts who suggest checking e-mail only once in the morning and once at the end of the day. Even in a department as large as ours (421 undergraduates), effective use of e-mail can eliminate barriers to communication, especially since we are located in a new section of the campus out of the mainstream of student traffic. Information about summer job postings, AIChE student chapter meetings, undergraduate research and scholarship opportunities, recommendation letters, and departmental details routinely zip across the lines to and from students. I want my students to be well informed and knowledgeable about campus and professional opportunities.

The final element of the office that reflects my advising philosophy is the door. It's open, and my desk chair is positioned so that I can see someone hovering around the entrance. Unless I'm doing something that must be completed at that moment, which is rare, I stop, smile, and say, "Come in, how can I help you?" The student usually says something like, "Are you busy?" Even if I'm in the middle of grading 40 essays for our undergraduate seminar course, checking blue cards for graduation, or contacting guest speakers for senior design, I say, "No, I'm not busy. Please come in and sit down." We rock. They talk. I listen. Often they leave saying something like, "Thanks for seeing me. I always feel better after leaving your office."

That's why I'm here.

SUGGESTIONS FOR ADVISORS

At this point the reader may be thinking, "Give me a break. Besides the fact that I couldn't possibly fit a rocking chair into my tiny office, I'm no Mother Teresa. And my graduate students already feel neglected, not to mention my own children." My purpose in writing this article is not to suggest that my style is the only style, or even the best style, but to encourage faculty to find their own style. The rockers and most of those little personal touches and the time I spend on advising (which is, after all, my main job) are nice, but they're not essential. Based on my experience, literature in the area of advising, and the feedback I have gotten from my students, I would offer the following suggestions on how faculty can make their advising more effective within the constraints of the other demands of the job:

- *Organize your department advising system to improve consistency and efficiency.* Depending on the size and structure of your department, consider ways to structure the advising process to allow faculty to best meet student needs. For example, I serve as the Coordinator of Advising and advise all the freshmen, double majors, and transfer students—in general, students who require "extra attention" and may have unusual or challenging curricular issues. This allows each of our faculty to advise a smaller group of students (typically 25 or less) who are doing the "standard" curriculum or a concentration in their area of expertise. This organizational structure improves advising consistency and efficiency, "giving back" time to other colleagues who are more focused on other key department functions such as instruction and research.
- *Use resources within your department to leverage advisors' time with students.* Our faculty call on me as a resource for information, as a referral if they feel the student needs additional attention, or as a "substitute" if they know they will be on travel status during advising time. I publish an annual advising handbook for both students and faculty with curricular information and frequently asked questions, and this information is also available on the departmental Web site. One of our staff members distributes hard copies of student degree audits at advising time and maintains a file for each student with

relevant information on their advising history. Don't feel as though you have to have all the answers yourself—use all the resources available to ensure that the time you do spend with each student is worthwhile.

- *Learn your advisees' names and use them.* Our Registration and Records Web site has an option that allows you to access a photo of each student—you can print out the pictures and names for easy reference. I take photos of students in my introductory class holding name tents, and study them in my office. A colleague photocopies his students' drivers licenses! Whatever works for you, use it.
- *When you are talking with a student, try to resist the temptation to peek at your watch or glance at your computer screen to read your latest e-mail—nothing sends the message faster that "I have better things to do."* (I have a large clock on the wall opposite the rocking chairs that helps me be aware of the time without seeming impatient or anxious to be rid of the student).
- *After you take care of the business of registration advising, take a moment to ask students about their summer plans, career goals, or hobbies.* This helps students feel that they are more than just a number, especially in a large department.
- *Let students know that you have a life outside of the office.* You could do this by posting an article or picture on your bulletin board, having a family or vacation picture on a desk, or displaying a memento from a recent trip or conference.

Finally, but most importantly, *care*. Findings by Wilson, *et al.*,^[8] indicate that faculty who are frequently sought out as advisors outside the classroom tend to provide clear clues about their accessibility through their in-class teaching style and their attitude. You can go to teaching workshops and even advising workshops to hone your skills, but simply caring is the foundation of all student interactions. No one cares how much you know, unless they know how much you care. You could be the one to make the difference in a student leaving, staying, or staying and enjoying the ride. Advisors rock!

REFERENCES

1. Baker, R.W., and B. Siryk, "Exploratory Intervention with a Scale Measuring Adjustment to College," *J. Counseling Psychology*, **33**(1), 31 (1986)
2. Pascarella, E.T., and P.T. Terenzini, "Patterns of Student-Faculty Informal Interaction beyond the Classroom and Voluntary Freshman Attrition," *The J. of Higher Educ.*, **48**(5), 540 (Sept.-Oct. 1977)
3. Seymour, E., and N.M. Hewitt, *Talking about Leaving*, Westview Press, Boulder, CO, p. 134 (1997)
4. Light, R.J., *Making the Most of College*, Harvard Univ. Press, Chapters 3 and 5, Cambridge, MA, (2001)
5. Wankat, P.C., "Current Advising Practice and Suggestions for Improving Advising," *Eng. Educ.*, **76**, 213-216 (Jan. 1986)
6. Wankat, P.C., and Oreovicz, F.S., *Teaching Engineering*, Chapter 10, McGraw-Hill, NY (1993). Available free as pdf files on the Web at <<https://engineering.purdue.edu/ChE/AboutUs/Publications/TeachingEng/index.html>>
7. Wankat, P.C., *The Effective Efficient Professor: Teaching, Scholarship, and Service*, Sections 7.2 and 7.4, Allyn & Bacon, Boston (2002)
8. Wilson, R, J. Gaff, E. Dienst, L. Wood, and J.L. Bavry, *College Professors and Their Impact on Students*, Wiley, New York (1975) □