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Advice to Authors for an Editorial Contribution
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Chemical Engineering Education

Chemical Engineering Education publishes editorials, usually invited, on subjects of current relevance to the community. The topic is normally controversial and the author is encouraged to clearly state his or her opinion on the issue and the rationale for the stated opinion. Past editorials topics include:

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Winter Issue October 1
Spring Issue January 1
Summer Issue April 1
Fall Issue July 1

Note that the Fall issue is dedicated to graduate education. Should you have any questions, please contact us at cee@che.ufl.edu
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USING WORD CLOUDS FOR FAST, FORMATIVE ASSESSMENT OF STUDENTS’ SHORT WRITTEN RESPONSES

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Imagine your department chair has just assigned you to teach Material and Energy Balances, a required course that has grown considerably in enrollment for the last several years. You taught it a few years ago and used ConcepTests[1] for in-class active learning with reasonable success. You plan to use them again this time around. You recently attended a professional development seminar that described the learning benefits of asking your students to write explanations and reflections. It sounds like a great idea, so you decide to have your students write explanations to justify their answer choices to their ConcepTests. You try it the first week of class. After class you are checking out the responses, plotting the answer distributions, and then it hits you. You see the 250 written explanations. It is going to take hours to read and analyze all of these explanations! If you don’t read them, will your students take them seriously? Will they continue to reflect and get the most out of them? If you do take the time to read all of them, what are you sacrificing? What part of your class preparation are you giving up? What do you do?

Many instructors have approached a dilemma similar to the one discussed in the vignette above. Sometimes it happens when you are first contemplating the implementation of a research-based instructional strategy and sometimes it comes, as in the vignette, only after the first implementation. This article presents a potential solution to the vignette dilemma of analyzing short written responses—the use of word clouds. Word clouds provide a visual representation of word usage and frequency. They offer a quick visualization of aggregate text responses to reduce the burden of information overload.[2] When combined with an audience response system, they afford instructors a way to easily analyze written explanations from tens or hundreds of students in a very short time.

At right is a word cloud summary of this article. Can you figure out the main point from the prominent words in the word cloud?
In this article, we describe how word clouds can be used for formative assessment in active learning. In particular, we discuss how they have been integrated into and used with the AIChE Concept Warehouse (CW). The CW is a web-based tool to help the chemical engineering education community more easily use active learning pedagogies.15 We focus on the ways word clouds afford improved instruction through the CW through their use as a formative assessment tool that can provide instructors and students with valuable, timely feedback. We illustrate the use of word clouds with evidence from two active-learning examples: student in-class responses to multiple-choice concept questions, during the first part of peer instruction1; and student responses to “muddiest point” reflection exercises,1,2 intended to assess the most confusing topic or concept presented in lecture. In addition, we explore other potential opportunities.

BACKGROUND

Active-learning pedagogies have been shown to improve student conceptual understanding.6 Active learning means more than engaging students in classroom exercises; activities should be designed around learning outcomes, promote student reflection, and get students to think about what they are learning.7 Formative assessment is one integral aspect of these pedagogies that helps meet these design criteria. Assessments that include students’ short written explanations8 or reflections9,10,11 can enhance learning.18 However, it is difficult to expediently examine written responses in large classes.

Word clouds, also known as “tag clouds” or “term clouds,” can be a useful analytical tool to summarize text data and provide meaningful interpretations.6 Word clouds have been found to be beneficial because they are “highly interpretable,” giving a direct visual representation of the content being measured.17 They have been used both as a research tool and as a teaching tool.

As a research tool, McNaught & Lam18 showed how word clouds can uncover themes in interviews consistent with those identified by other qualitative analysis methods. Similarly, word clouds have been used as a qualitative analysis tool in other cases.19,20 While word clouds are generally interpreted in terms of the most common words, attention to missing words or infrequent words can be just as important.17 The context from which a word cloud is created also plays an important role in the interpretation of the resultant word clouds,17 e.g., the phrase “energy balance” holds one meaning in a chemical engineering course and takes on an entirely different meaning in Oriental medicine.22

Educators have also begun to report the benefits of word clouds in teaching. Ramsden & Bate23 put forth a general working paper presenting word clouds as a useful teaching tool comparing different word cloud software and discussing aspects educators should consider. They note that data needs to be in a usable state (i.e., as electronic text) for word cloud analysis. In addition, they note the following potential limitations of word cloud software: spelling errors may not be taken into account; words that appear to be common may be eliminated even if they represent an important acronym, e.g., it versus IT; word clouds represent frequency, not necessarily importance; and word clouds often fail to group similar words. Ramsden and Bate23 suggest the use of word clouds as a complementary method to other research and teaching methods.

In practice, educators have described having students construct word clouds from pre-existing materials (such as speeches, quotes, and web pages) to summarize and promote reflection and discussion in many fields, including: accounting,24 social studies,25 teaching vocabulary,26 and theology.27 Word clouds have also been used in several ways for teaching reading and writing.28 In one example that resembles our use of “muddiest point” reflections, an instructor used word clouds to summarize students’ text messages in a high school English class to formatively assess what was learned in the previous class.29 In this article, we present how word clouds can be used in chemical engineering education. We illustrate how the CW affords automatic aggregation of students’ writing and word cloud construction. This system eliminates the need to manually collect and transcribe handwritten reflections in order to construct word clouds.

AIChE CONCEPT WAREHOUSE

The CW was used as the primary data collection tool for the examples reported in this article. It is a database-driven website facilitating the use of concept questions throughout the core chemical engineering curriculum. Currently the CW has more than 2,000 concept questions (ConcepTests) and 10 valid and reliable concept inventories available for searching, viewing, and using in courses. Instructor and student interfaces are available for use at <http://cw.edudiv.org>, and university faculty can obtain an account through this site. More general information about this tool can be found elsewhere.10 In this article, we focus on the word cloud feature that facilitated formative assessment.

For context, we provide a detailed description of the algorithm used to generate word clouds in the CW. A wide variety of word cloud algorithms are reported in the literature, e.g., some count the frequency of individual words while others count frequency of word pairs.30 Currently the CW summarizes the frequency of single words only. To generate the word clouds, the CW first aggregates all of the written class to formatively assess what was learned in the previous class. In this article, we present how word clouds can be used in chemical engineering education. We illustrate how the CW affords automatic aggregation of students’ writing and word cloud construction. This system eliminates the need to manually collect and transcribe handwritten reflections in order to construct word clouds.

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word size and color. Blue, bigger words are more frequent. Red, smaller words are less frequent. While some criticize word clouds for ignoring semantic relationships such as similar words, the algorithm the CW uses has been improved to ignore case differences and combines similar words like singular and plural forms.

**EXAMPLE 1: WORD CLOUDS IN CONCEPTTEST ASSESSMENT**

The first active-learning example we use illustrates the use of word clouds in the context of polling during peer instruction. Peer instruction is arguably the most well-known and widely used technology-mediated active-learning pedagogy in post-secondary Science, Technology, Engineering, and Mathematics education. It consists of a structured polling process where a concept question (also called a ConcepTest or ‘clicker’ question) is presented to the class. Students first answer the question individually. They are then encouraged to discuss the answer choices in small groups. Finally, they individually submit a final answer. This sequence is then typically followed by a class-wide discussion. The data presented below comes from the first individual answering where students are asked to explain in writing their choice for two sample concept questions.

**Methods**

Data were collected from two cohorts enrolled in a required, sophomore-level, undergraduate energy balances course at a large public university. Between 60 to 70 chemical, biological, and environmental engineering students provided written explanations for each of the two questions presented in this article. These students came from a subset of a larger study population, reported elsewhere. The lectures and recitations for both cohorts were taught by the same instructor, in the same room, using the CW to deliver the ConcepTests. The Institutional Review Board approved the research and participants signed informed consent forms.

Figure 1 and Figure 2 depict two isomorphic concept questions as they were presented to the students in their respective cohort; one cohort answered one question, the other cohort answered the other question. In isomorphic questions, students need to apply the same core
concept, but the questions have different surface features, like the balloon or piston in these questions, or what Smith, et al. calls “different cover stories.” To answer the questions correctly, ideally, students apply their knowledge of energy balances, recognizing that the work done by the gas on the surroundings lowers its internal energy and, therefore, its temperature. For this question pair, however, the correct answer can also be obtained from faulty reasoning using the ideal gas law. In that case a student may reason, since $PV = nRT$, as $P$ decreases, $T$ also must decrease. This reasoning process fails to account for changing volume, and is, therefore, classified as faulty reasoning.

**Results**

Figures 3 and 4 present the word clouds for the questions depicted in Figures 1 and 2, respectively. The left-hand side of each figure shows the answer options for the respective question. The middle contains the word cloud that was produced from the aggregation of written explanations for the corresponding answer option. The right-hand side contains a representative explanation given by a student that selected the corresponding answer. All written explanations for both questions were also iteratively coded, detailed results of which are presented elsewhere.

Students predominantly chose the correct answer for the piston question (Figure 1) using scientifically valid reasoning, yet students who answered the balloon question (Figure 2) correctly predominantly used faulty reasoning related to the ideal gas law. For the balloon question most students chose “remains the same.” They did so because they apparently thought that the balloon was “perfectly insulated”—no heat meant there could be no temperature change. The students that answered the piston question with “remains the same” thought that the decrease in pressure was compensated apparently thought that the decrease in pressure was compensated for by the increase in volume. Students who select this answer to the two conceptually similar questions do so using different reasons, and the word clouds capture this difference.

**So what can we learn from these word clouds?**

First, let us focus on the correct answer, “decreases.” The students who predominantly chose the correct answer for the piston question using correct reasoning have a corresponding word cloud in which the words “energy” and “work” can be seen. However, students who answered the balloon question correctly using faulty reasoning related to the ideal gas law, have a corresponding word cloud in which “energy” is present but “work” does not appear; terms like “$pv$” and “$nrt$” can be seen instead. In the case of the balloon problem, we see an example of when a missing word is as important as, or more so than, the words that appear. In this case, the word cloud without the word “work” suggests that even though many students chose correctly, they may still need attention regarding the role of work in closed-system energy balances.

We can also consider the word clouds associated with explanations for the distractors to provide insight into the ideas expressed by students who chose a wrong answer. The students that answered the piston question with “remains the same” thought that the decrease in pressure was compensated.

---

**Figure 3.** Multiple-choice answer options, word clouds, and representative explanations for the concept question depicted in Figure 1 (piston question).
for by the increase in volume. Notice that the words “pressure,” “volume,” “decrease,” and “increase” are in almost equal proportion. For the balloon question, most students chose “remains the same” since the balloon was “perfectly insulated”—no heat meant there could be no temperature change. Therefore, neither “energy” nor “work” appear in that word cloud. Again, the reasons for similar answers are different. In the case of the distractors, each distractor should have a particular misconception with which it is most associated, but it could have several. When combined with the instructor’s expertise and previous experience, a word cloud may provide an instructor with enough information to identify which misconception is most prevalent for the majority of students who chose each distractor.

To further help identify misconceptions, an instructor can click on any particular word in the word cloud to easily view the subset of the explanations that contain that word. For example, Figure 5 (page 196) shows the screenshot of the page that results when

The second example illustrates the use of Muddiest Point Reflections for formative assessment. In a Muddiest Point Reflection, an instructor asks students to write a brief, anonymous written comment describing the concept or topic that they found to be the most difficult to understand during class. With this information, the instructor can strategize to adjust his/her teaching and pedagogy to address issues specific to many students. The CW software allows word clouds of Muddiest Point Reflections to be available shortly after students have responded. It also provides links to words that allow filtered word clouds analogous to that shown in Figure 5.

**EXAMPLE 2: WORD CLOUDS TO EXAMINE MUDDIEST POINT REFLECTION**

<table>
<thead>
<tr>
<th>Answer Option</th>
<th>Word Cloud of Written Explanations</th>
<th>Representative Explanation (emphasis added)</th>
</tr>
</thead>
<tbody>
<tr>
<td>remains the same</td>
<td>balloon perfectly insulated remain heat increase volume temperature decrease change gas pressure pv nrt inside</td>
<td>the balloon is perfectly insulated so the temperature of the balloon does not change.</td>
</tr>
<tr>
<td>increases</td>
<td>nrt volume increase temperature pressure increase pv</td>
<td>pv=nrt, v is increase, so t is increase</td>
</tr>
<tr>
<td>decreases</td>
<td>balloon pressure temperature pv decrease gas energy molecules volume increase nt lower</td>
<td>Temperature must go down to maintain PV=nRT relationship.</td>
</tr>
<tr>
<td>need more information</td>
<td>volume pressure decreasing balloon pv nrt temperature ideal gas law change constant increase decrease</td>
<td>PV=nRT, or T=PV/(nR). Because P is decreasing, but V is increasing, we need to know how exactly they are related in order to know if temperature is increasing or decreasing.</td>
</tr>
</tbody>
</table>

---

**Figure 4.** Multiple-choice answer options, word clouds, and representative explanations for the concept question depicted in Figure 2 (balloon question).
Methods

Data were collected in several materials science classes at a large public university with class sizes of 40-45 students. Figure 6 presents a screenshot of the Muddiest Point Reflection as it is presented to students on their laptops, cell phones, or tablets using the CW. The Muddiest Point Reflection was assigned at the end of class and students could answer on their electronic devices; however, the assignment was allowed to be submitted up to six hours after class. Students were offered up to five percent extra credit on their final grade for answering at least 20 of the 24 Muddiest Point Reflections over the semester. These exercises have an estimated 65% response rate. In addition to the Muddiest Point Reflections, 33 students from one section answered a survey about the impact of word cloud use in the classroom. The data collected for this research was approved by the Institutional Review Board.

When the exercise was first presented to students, the instructor discussed with students the purpose of the exercise, both from a student learning and an instructor feedback standpoint. At the beginning of the class following each Muddiest Point Reflection submission, the instructor thanked the students for their submissions. In addition, the instructor showed the single word cloud aggregated from all student responses to the previous submission, presented student quotes, and led a discussion regarding the student learning issues. The discussion used the method of Socratic questioning in working toward resolution of the student learning issues. The instructor also reiterated that responses to the Muddiest Point Reflection would help improve not only the course for the current cohort of students, but for future cohorts as well.

Results

Figure 7 presents the resultant word cloud from an aggregate of all students’ Muddiest Point Reflections after the topic of failure in metals was covered in class. Figure 7 also includes representative quotes. This topic has important real-world consequences, since engineering systems such as airplanes, chemical plants, and bridges are susceptible to failures with consequent loss of lives.

So what can we and students learn from the Muddiest Point Reflection word cloud?

In the prior class discussion of this topic, the four main types of failures were described, along with the failure mechanisms, fracture appearances, and testing methods that have predictive capabilities. “Failure,” “mechanism,” and “types” were the largest words seen, indicating that failure types and associated mechanisms were the most prominent muddiest points as opposed to fracture appearances or testing methods. The major difficulty that a significant fraction of the students were grappling with was the connections between the different aspects of a given “type of failure mechanism,” which was clearly reflected in the size of the words in the word cloud.

A reading of the student comments confirmed the diagnosis that was first quickly highlighted by the word cloud. Because of this information, the instructor was inspired in the next class to create a well-detailed table delineating the characteristics of the failure mechanism types and features. The table included: a real-world example, conditions causing failure, mechanism of failure, fracture surface appearance, and test methods for predicting lifetime associated with different mechanisms. Most of the students vigorously took notes and copied the table during the discussion. This example illustrates how the use of word clouds in Muddiest Point Reflections helps the instructor improve and adjust instruction. The rapid feedback with the Muddiest Point Reflections and associated word cloud can have a significant impact on student learning.

Research has shown that addressing learning issues as quickly as possible with rapid feedback is very effective for improving motivation and learning.13

Figure 5. Sample filtered word cloud from the explanations aggregated into and summarized by the word clouds in Figure 3. They are limited to only the explanations that used the word “weight.”

![word cloud]

Chemical Engineering Education
Frequent feedback plays an important role in the progression of a learner from the level of “novice” toward “expert” understanding and performance in a given domain. In a review on the acquisition of expert skills, Ericsson, et al.³ cite one important condition for optimal learning and improving performance is that learners will receive immediate and informative feedback and knowledge of results of their performance on a given task. This is reflected by the response of the students to a survey about the use of word clouds.

Thirty-three students participated in an end-of-semester survey about the impact of the Muddiest Point Reflection word clouds in the classroom. Sixty-seven percent of those students agreed or strongly agreed that, “The word clouds helped me visualize what the most confusing concepts in the class were.” Seventy-six percent of the students agreed or strongly agreed with the statement that, “The word clouds informed me about issues other students were having with the class content.” For instructors, the word clouds and Muddiest Point Reflection provide a quick and measured diagnosis of student learning issues for adjusting current and future instruction. For students, the word clouds serve as a visual indicator of issues that they and others in class may be grappling with and they are more motivated to engage in discussion and dialogue in addressing those issues to improve their knowledge and learning on more difficult concepts and content. Thus, instructors and students are mutual beneficiaries of the use of word clouds in materials classes.

**What was the muddiest point in lecture today?**

![Submit Button]

**How muddy is it?**

- Almost Clear
- Slightly Muddy
- Moderately Muddy
- Very Muddy
- Extremely Muddy

**Figure 6. Muddiest point reflection as it was delivered to students.**

**Word clouds for other short written exercises**

In the previous two sections we discussed how word clouds have been used for specific types of exercises, ConcepTests and Muddiest Point Reflections. While further research is required to evaluate the utility of word clouds to examine other types of short written exercises, in this section we briefly explore a few other areas where word clouds may be beneficial. In general, word clouds can be used for any type of short written response. For example, Vigeant, Prince, and Nottis¹³⁶ describe inquiry-based activities for thermodynamics and heat transfer. In these activities students are prompted to predict results of an experiment before the experiment and explain their prediction in writing. The authors then have students run or observe an experiment. After experimentation, students compare results with their predictions in writing, and discuss with their peers. Finally they write answers to post-activity questions. Each of the writing steps presents an opportunity for word cloud use to visualize aggregate student responses. As their inquiry-based activities continue to be implemented at different schools in different contexts, word clouds might offer another quick way to examine if the students in these new contexts give similar responses to those in the original context. Other scaffolded activities that have a similar “predict - observe - explain” structure,¹³⁷ such as the interactive virtual laboratories recently incorporated in the CW, may also benefit from word clouds.

**Planned word cloud improvements for the AIChE Concept Warehouse**

For exercises like Muddiest Point Reflections and other short written exercises, the current word cloud analytical algorithm may be sufficient. However, this type of analysis may benefit from including the option of using word pairs, as a basis, an option we are currently exploring. Word pairs, if they maintain word order, might highlight instances where the order of the words is as critical as the individual words themselves. In addition, we are considering modifications to address one of the concerns reported by Ramsden and Bate; to prevent the elimination of seemingly common words with special meanings (it versus IT) we intend to incorporate a custom list in which instructors can identify words to exclude or words to include.

**Conclusions and implications**

Active learning can help students develop deeper understanding of chemical engineering principles. While multiple-choice ConcepTests...
are useful, we advocate for including student writing in learning activities as well. Writing explanations and reflections can help students organize their thinking and explicitly reflect on what has been covered. These types of assignments also provide information that faculty can use to focus instruction. Examining students’ writing reveals their faulty reasoning and misconceptions, and can help the instructor identify concepts and topics that are difficult.

In this article, we demonstrate that word clouds can provide a quick analytical technique to begin assessment of student written explanations and reflections. The AIChE Concept Warehouse automatically generates word clouds and can facilitate collection and analysis of student writing, even in large classes. Unlike external applications like Wordle where text needs to be manually entered, word clouds are automatic and quick. However, even with automation, instructors still face the challenge of interpreting the information provided; consequently, we are also working to improve and better integrate word clouds and include other analysis options into the AIChE Concept Warehouse. Our goal is to help make deep, concept-based learning more effective for students and easy for faculty to implement.

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REFERENCES

Introduction to Chemical Engineering Reactor Analysis: A WEB-BASED REACTOR DESIGN GAME

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Since the beginning of the chemical engineering profession in late 19th century, ChE faculty have been frustrated when attempting to explain their field to college freshmen or high school students. When looking for information about a college major, high school students should be informed of the opportunities that ChE can offer in terms of applying chemistry, physics, and biological sciences to engineering problems. Freshman ChE students should be given an effective introduction to what they are going to encounter in their four years of education. Whereas civil, electrical, and mechanical engineers can illustrate their profession by having students construct model bridges, simple circuits, or a simple mechanical device, chemical engineers cannot ask students to build a “simple” model chemical plant.

We have developed an approach to address this issue. Our approach involves an interactive website and a business simulation game that demonstrate how to model a lab-scale experiment and use the results to design and operate a commercial chemical processing unit. When we applied this approach with high school students and freshmen ChE students at the University of Massachusetts, Lowell (UML), we received very positive student feedback. We believe that this effective approach will greatly aid in science, technology, engineering, and math education, which has been strongly emphasized in recent years.

Specifically, we implemented the Chemical Reactor Analysis Design (CRAD) Game, created by T.W. Fraser Russell of the University of Delaware and Becky Kinney of Moonlight Multimedia. This game utilizes a new teaching approach with a “technically feasible design” (TFD). It was originally developed and operated with FORTRAN software. A combination of lectures and computer lab experience—employing personal computers (PCs) and an interactive website—was used to provide students with a hands-on approach to problem solving.

The object of the game was to design a continuous-flow stirred tank reactor (CSTR) to produce a product and compete for market shares against three other companies producing the same product. Figure 1 outlines the ChE analysis required to

Figure 1. Technically feasible design schematic.©

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solve the problem, as well as the model development, model behavior, and comparison with experimental data. This last step is not trivial to perform, and is what makes engineering an art. All of the steps in the analysis must account for the objectives of the problem. In the game, constraints and uncertainties are illustrated by the competition, marketing, and financial aspects of the proposed process.

**STUDENT PARTICIPATION**

We tested our approach in two different settings for two different audiences: college freshmen at UML and high school juniors and seniors at Lowell High School in Lowell, MA. The approach varied due to the different math and science backgrounds of each group. The CRAD Game was used for three years at UML and one year at the Lowell High School.

**Freshman students**

The **Introduction to Chemical Engineering Course** at UML is a 3-credit, 3-hour-per-week required course for all incoming ChE students and is offered in the Spring semester. The class enrollment is about 80 students. The course is designed to give students an overview of the ChE curriculum and solidify their interest in the profession at an early stage in their education. The course lasts 13 weeks and consists of seven modules, ranging from 1 to 2 weeks per module. The CRAD Game was covered as one of the 2-week modules. Other modules describe options that are available in our program, such as biological engineering, nuclear engineering, and nanomaterials engineering.

During the module that covered the CRAD Game, a general lecture was given each week to all 80 students. After the lecture, students were divided into four groups of approximately 20 students each. They participated in a 2-hour hands-on computer laboratory session, in which each student had access to a PC. Students were expected to derive all of the pertinent model equations. We used the reactor as an example, to emphasize the importance of obtaining lab-scale experimental data, modeling, and subsequent scale-up. However, the CRAD Game was not meant...
While inside the reactor, A is converted to D. Although we do not yet know the nature of the conversion, we can see where the rate plays into a Level III analysis of the system.

<table>
<thead>
<tr>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_A$ (g/moles liter)</td>
</tr>
<tr>
<td>$\Delta t$ (minutes)</td>
</tr>
<tr>
<td>$r_{A-}$ (g/moles liter min)</td>
</tr>
<tr>
<td>$V$ (liters)</td>
</tr>
</tbody>
</table>

Drag terms from the nomenclature panel to fill in the blanks.

A in system at time $t + \Delta t$:

A in system at time $t$:

moles of A that disappear from $V$ during time $\Delta t$:

To obtain the derivative of $C_A V$ with respect to $t$, drag the expressions above into the equation below...

$$\frac{(C_A V)_{t+\Delta t} - (C_A V)_{t}}{\Delta t} = \frac{r_{A-} V \Delta t}{\Sigma}$$

...divide by $\Delta t$, and take the limit as $t \to 0$:

$$\frac{dC_A V}{dt} = rV$$

Well done!

The web-based design game presented here has its roots in a pre-PC work. The same approach was used, but the students handed in papers and the results were entered into a FORTRAN program. The use of PCs and the web enables a much more effective interactive learning approach. Many excellent papers have described the development of web-based teaching tools in ChE, including a process dynamics and control exercise, as well as a virtual laboratory for chemical experiments. Newell\(^7\) and Vestal\(^8\) created web-based active-learning games that addressed different motivational styles and were loosely based on TV series. While similar to their approach, our game addresses economic and business aspects in addition to technical considerations. ChE educators have gone to high schools to lecture interested students in ChE curricula, as a part of outreach.\(^9\)-\(^13\)

**INTRODUCTION AND REVIEW OF CHEMICAL REACTOR ANALYSIS**\(^14\)

In the college freshman course, the first lecture was a general introduction to reactor design. The emphasis was on the challenges of transitioning technology from lab-scale batch reactors to commercial-scale production in continuous flow reactors. The roles that experiments and modeling play in the scale-up and design were discussed, as these roles are key background information for using the website and playing the game.

The object of the game was presented as follows: "How can a chemical engineer design a reactor to manufacture a chemical, D, produced by the following chemical reaction:

$$A \rightarrow D$$  \hspace{1cm} (1)\n
Students were tasked with designing and building a CFSTR. The reactor volume and the flow rate of the feed stream needed to be specified by applying the conservation of mass principle for each species and deriving the model equations. In addition to technical considerations, the amount of product that can be sold was influenced by the actions of other companies competing for the same market. This uncertainty was included in the game.

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**High school students**

High school students included in this study were enrolled in either an engineering or physics class at Lowell High School, and had an interest in chemical engineering or engineering in general. Eleven high school students voluntarily participated in this study, through a group that met once weekly after school for four weeks to test the CRAD Game. During the first week, a 45-minute lecture was presented in which the students were given the model equations (rather than having to derive the equations themselves). For the subsequent three weeks, the students met in a computer lab, with one PC for each student.
After the lecture, students were divided into four groups and began the hands-on computer session. Each student had access to a computer and opened the Introduction and Review of Chemical Reactor Analysis, Activities, section of the website. Figures 2 to 12 are screenshots reproduced from the game website.

Chemical engineers depend heavily on experiments, done by themselves or by others, that form the basis of any commercial-scale operation. These experiments need to be analyzed to determine the reaction parameters. The present case considered a single constant, \( k \), obtained in a laboratory batch experiment in a flask at constant temperature. The amount of A (or D) was measured as a function of time, as shown in Figure 2.

As a first step, students had to determine the reaction parameters by deriving the batch reactor model equations from the conservation of mass and the nomenclature given in Figure 3. To develop the model equations for the batch reactor, the students used a drag-and-drop procedure on the website. They moved the symbol from the left-hand side of Figure 4 and placed it with the correct word statement on the right-hand side. If the student placed the symbol with the wrong word statement, then the program kicked the symbol back to the left-hand side, thus providing immediate feedback. The model equation was solved to obtain the specific reaction rate constant \( k \) for the reaction \( A \rightarrow D \), assuming a first-order reaction.

The next step was transitioning this knowledge to large-scale operation. Batch experiments are done at the laboratory scale in flasks and beakers, which are too small to produce large, commercial-scale quantities. It is the role of a chemical engineer to analyze and scale-up batch data to produce
commercial-scale quantities of a chemical. For this step, students had to derive the model equations for a CFSTR from the conservation of mass equations for components A and D, using the nomenclature in Figures 3 and 5, as well as the drag-and-drop procedure in Figure 6. The resulting model equations were as follows:

\[
\begin{align*}
\text{Component A} & : 0 = qC_A - qC_A - kC_A V \\
\text{Component B} & : 0 = kC_A V - qC_D
\end{align*}
\]

After the students had derived the model equations, the website illustrated how the equations could be applied via a TFD problem. A TFD is a design that defines the size of a piece of equipment (in this case, the reactor volume) to meet a stated production rate (in this case, for D). In so doing, it initiates an analysis of factors affecting optimal design. This critical teaching tool is described in detail in a previous publication.111 The TFD question on the website (Figure 7) was as follows: "Using the model equations above, determine the reactor volume (V) if the demand for D (qC_D) is 10 gmoL/min, given that the feed concentration of A (C_{AF}) is 0.2 gmoL/L and the reaction rate constant (k) is 0.005 min^{-1}." Eq. (2) can be rearranged as follows:

\[
V = \frac{qC_D}{kC_A}
\]

Students were asked to determine the reactor volume individually, while being closely monitored by the lecturer and teaching assistants who walked around the computer lab. There were two equations [Eqs. (2) and (3)] with three unknowns (reactor volume, V; outlet concentration of A, \(C_A\); and flow rate, q). After considerable individual discussion and trial-and-error manipulation of the equations, the students, with the help of the instructor, realized that they could not solve for V without knowing \(C_A\) or q. The class then discussed which variable was best suited to make a realistic initial guess for its value. Picking a flow rate would be a more difficult choice because the upper and lower limits of q are not obvious at first sight without manipulating the two equations. On the other hand, \(C_A\) needs to be between the feed concentration (\(C_{AF}\)) and zero. At high conversions, the value of \(C_A\) approaches zero, requiring infinitely large reactor volumes. Any other value of \(C_A\) requires a separation unit after the reactor to purify the product and/or recycle unused reactant. \(C_A\) cannot be higher than the concentration of A in the feed stream (in this case, 0.2 gmoL/L).

For each value of \(C_A\), different values of V and q will be obtained; in other words, there is no one "right" answer. The value should be selected depending on the design and other criteria for the process. This concept can be a difficult one for students to understand because until now, their entire educational experience has included problems with only one "right" answer. Students can go through this problem (in Figure 7) as many times as they want until they are comfortable with the concept. Each time they repeat the problem, the computer changes the parameter values. When a TFD is completed, the simulation on the web allows students to have an interactive experience, in which they can change V and q and visually observe how the production of D is affected by the different values. A separation unit is included for better visualization of the process. Figure 8 is a screenshot from the simulation that shows this interactive exercise.

At the end of the lab session in the first week, the students were assigned homework on the TFD under the Non-Graded Activities option on the website. The homework was intended to solidify the concepts covered, as well as to help the students feel comfortable with the use of the website and the simulation.

**PLAY THE GAME**

During the lecture hour in the second week, the concept of and factors affecting process design were discussed, as shown on the website. Students were given a brief introduction to the economic and marketing aspects of design. Again, the lecture hour was followed by a 2-hour hands-on computer lab session consisting of 20 students per group.
the manufacturing cost was realistic and derived from actual experience. Students were given some time to practice with the Activities website and calculate the profit they could make based on their design.

**PLAY THE GAME: THE COMPETITION[15]**

The Graded Activities and Activities sections are the same program, with the exception that tasks in the Graded Activities section are completed sequentially, and the user cannot go back to change/revise a design parameter. The first two questions reviewed what the students learned in the first week. Students were asked to calculate the volume and flow rate of a reactor for a given CA. Then, they were asked to calculate the profit they would make for this particular design, assuming that they could sell all that they produce. Students were permitted to repeat the activity as many times as they wanted before starting the competitive game, to become comfortable with using the website. Whenever a student attempted a Graded Activity, a new set of input parameters was given; thus, no two trials were the same. A screenshot of the Graded Activities section is shown in Figure 11.

The competitive game was designed so that there were four companies competing for the same market share of chemical D over a 5-year period. Initially, each student played against three other computer-generated players. The company (student) with the highest profit at the end of the fifth year won the game. Students were encouraged to pick a name for their company.

To design the reactor, each company (student) had to determine the market share they were going to pursue and the year they were going to base their design on, using the demand curve for product D. These decisions are critical uncertainties in any process design. The strength of the game is that these uncertainties are incorporated in the simulation.

The game followed a similar course as the Graded Activities. Each company must first start with lab experiments to

---

**Figure 9. Demand curve for product D.**

<table>
<thead>
<tr>
<th>Yearly Manufacturing Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Capital Cost Depreciation, Maintenance, Operation, and Waste Disposal = $45.00/ reactor volume (liters)</td>
</tr>
<tr>
<td>- Raw Material Cost = $0.20/gram-mole</td>
</tr>
<tr>
<td>- note: unconverted raw material can not be recycled.</td>
</tr>
<tr>
<td>- Cost of storing unsold inventory = $0.10/gram-mole</td>
</tr>
</tbody>
</table>

**Figure 10. Financial summary of game.**

Students were shown the market demand curve of component D for a period of five years (Figure 9) on the website. This demand curve is slightly different than the one normally seen in an economics course; specifically, it shows how the demand for D will vary with time, in an effort to quantify production and selling price. The website gave a simplified version of manufacturing cost (Figure 10). Capital equipment costs (e.g., reactor, separation unit, pumps, valves, piping) and yearly manufacturing costs (e.g., maintenance, operation, waste disposal) were considered to sum up to an approximate value of $45 per reactor volume (in L). The website specified the raw material cost, cost to store unsold inventory, and sale price of product D. Although presented in a simplified manner,
determine the rate constant k.

Once a reactor size was selected, it could not be changed over the 5-year production period. However, the flow rate can be changed from year to year to influence the profits. Students who cannot do these steps by themselves have the option of “hiring” help (i.e., consulting chemical engineers) to make these calculations for them. However, they will have to pay these employees a salary, which will appear as a “debt” in the first year. A screenshot from the game illustrating this aspect is presented in Figure 2.

Students were able to view the year-end report for their companies after each year, and determine whether the flow rate of the feed stream should be changed. This decision was based on several factors, such as the market share, profit, and amount of unsold inventory. At the end of the 5-year period, students printed out and handed in their final report for all five years. A sample of the year-end report is shown in Figure 12. In each lab section, students with the four highest profits at the end of the five years were selected and played against each other on the same computer. The winner of the second round of the competition received a small prize. Other students had the option of playing against three other students if they wished. The outline of the two weeks of the CRAD Game course is summarized in Table 1.

HIGH SCHOOL JUNIORS AND SENIORS

Whereas college freshmen spent part of the hands-on computer laboratory sessions deriving the model equations, the high school students were not asked to derive the batch reactor and CFSTR mass balance equations. The derivation was explained in detail by the instructor and the final equations were given to students. The remainder of the procedure for using the website and playing the game was the same with the high school students as with the university freshmen.
STUDENT FEEDBACK

All three authors of this article were present during the computer sessions of the class. Because the class size was small (20 students), it was possible to obtain immediate feedback while the students were learning to use the website, derive the equations, and make the required calculations. The students showed great interest in the game, and they were all actively engaged in the class. The web exercises "made the problems easier to understand with the visual aid" of the game. Each student had his or her own computer, allowing students to understand concepts at their own pace. Interactions between students and with the instructors were encouraged.

At the end of the second week and at the conclusion of the game (March 2012 and 2013), the ChE freshman students were asked to respond to the following questions:

A. Did the lectures provide an effective introduction to the exercises that followed?
B. Did the non-graded and graded activities prepare you for the game?
C. Was the game effective in demonstrating what chemical engineers do and the challenges they face?

Students were asked to rate their answers on a scale from 1 (poor) to 5 (excellent). The results of the survey are presented in Figure 13, in which the percentage of students giving a particular rating for each question is shown as a bar graph.

Most students rated their experience as positive, with more than 80% of students giving high ratings (4 or 5) to all questions. For Question A, 81% of students rated the lectures as an effective introduction for the exercises that followed, and 83% of students found the graded and non-graded activities to be useful. About 89% of the students gave the highest rating to the game being an effective learning tool. Overall, students "enjoyed practicing [problems] using real-life-based situations."

Involvement in the study and playing the game might have had some influence on the choices made by high school students, as five of the 11 participants went on to study engineering in college. However, in addition to the game, these students had other exposures to engineering concepts, which were included in the physics course and a separate engineering course taught by Mr. Anthony Iarrapino and Dr. William Jumper in their high school. Although the high school students responded favorably to the after-school class and game, we felt that more time was required to make it as effective as it was for the freshman engineering students.

ACKNOWLEDGMENTS

The authors express sincere gratitude to Dr. William Jumper and Mr. Anthony Iarrapino of Lowell High School for arranging to work with their students and help in playing the game.

REFERENCES

14. [http://www.mht.che.udel.edu/static/activities.html]
15. [http://www.mht.che.udel.edu/graded/activities.html]
THE MURKY CRYSTAL BALL

Richard M. Felder

In 1968 I was in the second year of a two-year postdoc at Brookhaven National Laboratory, looking for a faculty position. I got an invitation to apply for a vacant position at North Carolina State University, and even though I believed that civilization as we know it pretty much ended south of New Jersey, I went to Raleigh for an interview. In my first morning on campus I was with Jim Ferrell, the Department Head, chatting about my goals and interests and finding out what I could about life in the wilderness, when an elderly gentleman walked into the office and Jim said “Rich, I’d like you to meet Warren McCabe.”

In my mind Warren McCabe wasn’t a real person—he was the legend who co-created a graphical method for designing distillation columns back in ancient times (actually, 1925). It felt like Jim was introducing me to George Washington or Socrates. I bit my tongue before blurting out “Is he still alive?” and responded with one of the usual pleasantries.

I just looked McCabe up on the Web and learned that he was born in 1899. I did the math and figured out that he was 69 years old when I met him that day. I was born in 1939. Do the math. I’m going to take a nap now. Talk among yourselves for awhile.

OK, I’m back. In 1968, I was 29 years old. If you had asked 29-year-old Warren McCabe to predict what an engineering professor’s life would be like in, say, 15 years, he would probably have guessed that it wouldn’t be all that different and he would have been right. If you asked 29-year-old Richard Felder to make predictions in 1968 about what 1983 would be like, it would have been a different story. There were computers in 1968, but that was it for technology. We were all still doing our basic calculations with slide rules—I didn’t get my HP-35 until 1972. E-mail began in 1972. The term “word processing” was used for the first time in 1974, and a few years later the first word processors that weren’t just add-ons to typewriters appeared. (If I’ve lost you, feel free to Google “typewriter.”) The first modern spreadsheet program (VisiCalc) and the first commercial antecedent of PowerPoint (BRUNO) both appeared in 1979, and the IBM PC came along in 1981. There were Internet-like connections between some universities starting in the early 1970s, and the word “Internet” showed up in 1982. Good luck predicting all that in 1968.

But just to prove that wisdom doesn’t necessarily come with extreme age, I’m going to make a few predictions about engineering education 10 years from now—long enough for the future to be far from predictable, and short enough to give me a fighting chance of still being around to be humiliated when I turn out to be wrong about everything.

• **Goodbye, straight lectures. Hello, flipped classrooms.**

In 10 years you’ll still be able to walk down the hall of an engineering school building, poke your head into a random classroom, and see an instructor showing PowerPoint slides to a nearly catatonic class. The odds that that’s what you’ll see will be a lot lower, though. You’re more likely to see students clustered in groups working on an assignment or project, or sitting over a tablet or laptop computer viewing a video or simulation or multimedia tutorial or solving a problem or...
writing a report. Their instructor will have discovered that her students could learn the straightforward course content themselves from well-designed online materials and then learn the hard stuff actively in class, and so she flipped her class. By 2024, most classes that aren’t fully online will be flipped.

• Goodbye, math-heavy curriculum.

The math that occupies such a large part of most current undergraduate engineering curricula—three semesters of calculus, analytical solutions of boundary-value problems, Laplace and Fourier-domain analysis, tensor calculus, and so on—will migrate primarily to graduate and undergraduate honors courses. It will be replaced by training in more of the skills most engineers will actually need in coming decades—critical and creative thinking, economics and business, and those “soft” skills like communications and teamwork that ABET muscled into the curriculum in 2001.

• Goodbye, textbooks.

Forget about 10 years from now—a 700-page book that costs students upwards of $200 is already a dinosaur. (I freely admit that I’m currently involved in creating the fourth edition of a stegosaurus.) A $50 electronic version of that dinosaur with pages viewed and turned on a computer screen is also a dinosaur, perhaps from a later period but equally destined for extinction. The future—the near future, not the distant future—belongs to interactive instructional technology that makes students active participants in the learning experience and not just passive recipients of information.

• Hello, faculty development.

The absurdity of turning new faculty members loose to start and build research programs and teach without so much as five seconds of guidance on how to do those things will finally dawn on administrators. Many schools will start providing discipline-based faculty training and mentoring, cutting a full three years from the average time their new faculty members take to reach their potential for research productivity and teaching effectiveness. (That development has already started to take place, and the outcome isn’t speculation—it’s already been demonstrated.)

• Hello, corporate university model. Goodbye, tenure.

A large and growing number of universities now view themselves as businesses and unhesitatingly sacrifice educational quality for short-term revenues. That trend will continue. Retiring tenured professors will be increasingly replaced by contracted instructors. Lectures will be delivered to larger and larger classes by fewer and fewer professors, supplemented by recitations led by those contracted instructors and graduate students. The resulting cost savings will mainly go to raise top administrators’ salaries and benefits and hire more associate and assistant provosts and deans. I hope this gloomy picture is an unrealistic worst-case scenario, but I would still bet on it.

• Hello, MOOCs.

It’s getting popular to write off MOOCs (massive open online courses) these days. In journal articles and white papers and faculty meetings, pundits assure us that MOOCs are just a fad and will disappear within a few years.

Wrong! The technology for presenting online courses and getting online students actively and interactively engaged is rapidly improving. In the coming years the most skillful and charismatic instructors in the world will collaborate with expert software designers to create dynamic lecture clips, animations, simulations, interactive tutorials, and virtual labs run by virtual student teams. As those developments take place, more and more degrees will be awarded by accredited MOOC-based and other online programs for a fraction of the cost charged by brick-and-mortar campuses, and more and more students will vote for the online’s with their feet.

• Goodbye, many traditional universities—but not all of them. (Hopefully, not yours.)

Many traditional schools will continue to follow the corporate model described two bullet points ago. They will not be able to compete for students with those well-designed, well-implemented, and much less costly online programs, and some of them will no longer be with us in 10 years. Other schools will take as their primary mission equipping students to function as skilled and creative professionals, critical thinkers, and well-educated citizens. Those schools will hire faculty capable of fulfilling that mission; give them reasonable facilities to teach in (goodbye, 700-student classrooms); and provide recognition and rewards to the instructors who succeed. They will be able to claim and prove that they provide a better education than online programs will ever be able to provide, and they will still be here in 10 years and in the decades that follow. I’d bet heavily on this one. □
Numerous studies have shown that using active learning methods in class improves student learning. The fraction of engineering faculty who adopt these methods is small, however, and the two key barriers most often cited in faculty resistance to adopting best teaching practices are:

1. Lack of resources for utilizing active-learning techniques. Because most faculty are severely time-constrained, they tend to adopt teaching approaches that rely on previously used materials, especially old course notes that use a lecture format. Developing new content for active-learning approaches takes significant time.

2. Lack of experience or familiarity with active-learning techniques. A closely related problem is that many instructors are simply unaware of proven practices in education, and have not been trained on how to use them, nor do they have time to study effective teaching approaches. However, the central philosophy of our approach is that, like students, instructors learn best by doing. That is, they will be most likely to incorporate active learning into their teaching philosophy for future courses if they have used best practices in a loosely guided way.

Therefore we have developed an easy-to-use course package to fill the gap between teaching innovations and their implementation in engineering education in order to improve student learning and engagement in chemical engineering courses. Although this course package is aimed at encouraging a new generation of early-career faculty to use active-learning methods in their teaching, it also allows established faculty to more easily adapt their teaching. This course package contains complete class notes that utilize ConceptTests with peer instruction and they are designed for instructors to use student response systems (clickers). The materials are
presented in Microsoft OneNote so they can be used directly in class. In addition, they are designed to be used in a flipped classroom,[15-17] where content is delivered outside of class using textbooks, screencast videos, and pre-class homework sets, so that class time can be used for active learning. Thus, the course package incorporates suggested screencasts for each class. The course package also contains three to four semesters of assignments and exams, all of which can be modified. Suggested multiple-choice or short-answer reading quiz questions are provided for each class to help the instructor motivate students to be prepared for class. They can be entered into an online classroom management system (e.g., Blackboard, Desire2Learn) so that students can complete them before class, and faculty can use their responses to focus their teaching efforts during class [Just-in-Time Teaching (JiTT)].[18] The course package also contains reading quizzes and learning goals for each chapter. It includes teaching hints, tips on creating and grading exams, recommendations for dealing with various classroom and student situations, an example syllabus and schedule, and screencasts on how to use the materials effectively.

The course package focuses on integrating active-learning methods into the course; each class is designed using ConcepTests. These conceptual multiple-choice questions are used during class to improve student understanding of the important concepts and to challenge their misconceptions.[19-21] Studies have shown that using ConcepTests and peer instruction[1-7] instead of standard lectures dramatically improve functional understanding (“ability to interpret and use knowledge in situations different from those in which it was originally acquired”).[22] Typical science and engineering courses emphasize solving quantitative problems, and thus students have difficulty applying the knowledge to new situations.[23] Student responses with clickers provide the instructor (and all students) immediate feedback about student understanding, so that the instructor can use class time to concentrate on confusing concepts. This approach creates a more engaged learning environment, and allows students to determine how well they understand key concepts. It also allows them to learn from as well as teach their fellow students. Students prefer this mode of instruction; class discussions are livelier, attendance is higher, and students are more motivated to be prepared.[1-9]

In flipped classrooms, the traditional approach of presenting lectures in class and having students solve problems at home is inverted. Information delivery can be done through screencasts, which are short videos that include narration by an instructor, and are made using software that captures the images on a computer screen. Screencasts introduce a topic, solve an example problem, explain a concept or a diagram, demonstrate the use of course software, or review for an exam. Interactive screencasts have been prepared that allow students to assess their conceptual understanding through interaction with a screencasts-based ConcepTest. Flipped classrooms can be implemented by aligning appropriate screencasts to each class, along with questions to answer while watching the videos. Some reasons to use screencasts include:

- **They improve student learning:** 1) directly, as indicated by studies in literature,[19-27] and 2) indirectly, by freeing up class time for active learning exercises (e.g., ConcepTests, clickers, peer instruction, group exercises) that improve student learning.[1-52]

- **Students watch them even when screencasts are not assigned.** Statistics from our online screencasts (1.8 million views in the last 12 months) show extensive screencast use. Any learning materials that result in students spending more time on a course are likely to result in more learning.

- **Student feedback is overwhelmingly positive.** Although students' opinions are not sufficient to indicate how useful screencasts are for learning, anything that has such positive feedback and focuses on course learning goals while motivating students to take initiative in their learning is beneficial.

### COURSE PACKAGE DESIGN

The overall course package structure is a digital notebook that combines textbook resources with those of a practiced professor. Combining active-learning tools into one central, user-friendly notebook provides faculty with a valuable teaching tool. In addition, the course package allows for modifications and updates as classes and resources are improved. Microsoft OneNote is used to host the course package as it is user-friendly, simple to learn, easy to access because it is a component of Microsoft Office, and can be used in class with a tablet PC instead of PowerPoint. Thus, class presentation materials, homework assignments, exams, and instructor explanations are all included in one educational suite. Requesting free access to the restricted course package is done through the “Instructor Resources” webpage at <www. learncheme.com>.

Implementation of the course package is straightforward. A new faculty member simply opens a section, becomes familiar with the topic (i.e., the learning goals, student misconceptions, areas of difficulty), and then uses the class notes that utilize active-learning methods. For example, a section for a given day would include pre-class reading questions, course notes to use in class (ConcepTests, explanations, diagrams, etc.), hyperlinks to online resources, and suggested homework problems. Information for distribution to students is assembled so that it can be easily configured to post online. Since the notebooks are dynamic, they provide desired instructor flexibility[11]; faculty can easily customize them by removing or adding to the sections and pages, building assignments, and modifying what to present in class. Additional sections on active learning and good teaching practices help frame the importance of these methods.
This OneNote notebook for chemical engineering thermodynamics is based on the textbook by Elliott and Lira Introductory Chemical Engineering Thermodynamics, 2nd Edition, but the material can be readily modified and used in a different order for use with other textbooks. It is designed to be used for a one-semester comprehensive course, but it contains additional material that can be used for each chapter so that it can be used for a two-semester course.

Lecture Notes Explanation: Screencast explaining how to use the class notes before and during class.

Each chapter is in a separate OneNote section that contains the following:

- **Class notes for each day:** A set of notes for each day’s class, these consist of ConceptTests and active learning exercises. A day’s notes is complete so it can be used directly in class, but the OneNote page can also be easily modified by the instructor.
- **Instructor hints:** Each page containing class notes is divided vertically into three sections:
  - Class notes to be used directly in class
  - Answers to ConceptTests, explanations of this answer
  - Additional ConceptTests

This just points out that we have to choose a reversible path to calculate the entropy using the equation. Because entropy is a state function, the entropy change between states will be valid for all other paths that connect those states, but we can only easily calculate entropy changes for a path that is reversible. As we’ll see later, it’s for this reason that we often calculate performance for a reversible compressor or turbine before figuring out how an irreversible (not 100% efficient) unit will perform.

**Figure 1.** Example screenshot showing overview of information provided in each course notebook.

**Figure 2.** A class page in OneNote. Tabs at the top are for chapters. Tabs at right contain learning goals, links to screencasts, notes to be used in class, reading quizzes, handouts, and links to interactive simulations.

as well as explain to an instructor the reasoning behind the proposed approach. Once five or six weeks have passed, he or she opens a section that contains six to eight sample exams with solutions in a format such that individual questions can be compiled/configured(modified) to create an original exam. Figures 1 and 2 are screenshots of the notebook, which is organized by the table of contents of the textbook selected for use.

**COURSE PACKAGE CONTENTS**

The thermodynamics course package was developed for one textbook initially, but similar packages are being developed for other thermodynamics textbooks. The course package contains the following:

- **Daily class notes:** A set of notes is included for each day; this consists of announcements, daily topics,
Reading Quizzes

5.1 The Carnot Steam Cycle

What does the area inside the T-S diagram equal to?

A. The heat added to the turbine.
B. The net work done for one cycle.
C. The net intake of energy as heat for one cycle.
D. The total entropy change for one cycle.

Answer: C

5.2 The Rankine Cycle

What statement correctly describes the difference between a Carnot cycle and Rankine cycle?

A. The Carnot cycle is an isentropic process, but the Rankine cycle is a isenthalpic process.
B. The total energy input in the Carnot cycle is more than that in the Rankine cycle.
C. In the Rankine cycle, vapor leaving the boiler is superheated, but it is not in the Carnot cycle.
D. The total entropy change is the same for both cycles.

Answer: C

Answer C can be confusing since the Carnot cycle does not have a phase change. There is vapor in the Carnot Cycle but it is just not superheated.

When steam is used in an energy cycle, why is the steam not compressed and then fed to the boiler as a high pressure gas?

Figure 3. Reading quiz questions for chapter 5 material. These align with the learning objectives and prepare students for in-class activities.
Assignment 4

Assignment 4  Due: Assignment to be completed in assigned homework groups.

1. E-L 2nd, 6.2 (e), (d), (f), (b)
2. Describe an experimental setup and the experiments that will measure the partial derivative of enthalpy with respect to pressure at constant temperature for a non-ideal gas.
3. Design a vapor compression refrigeration system to cool a system to -5 °C with the capability for up to 20 kW of cooling. You have a reservoir at 20°C to reject heat to. Refrigerants and their properties can be found at http://webbook.nist.gov/chemistry/fluid/
4. An ideal Rankine cycle operates with the following design: 100 kg/s of steam enters a turbine at 30 bar and 500°C and is condensed at 0.1 bar. Determine the power produced and the efficiency of the cycle.
5. Evaluate the partial derivative of H with respect to V at constant T and P for a pure species that obeys the van der Waals equation of state.
6. Present a physical process on a system that is described by the partial of U with respect to P at constant S. Describe the process as completely as needed. Based on this process, do you think this partial derivative is positive, negative, or zero? Justify your answer.
7. Gas A expands through an adiabatic turbine. The inlet stream flows in at 100 bar and 600 K, while the outlet stream is at 20 bar and 445 K. Calculate the work produced by the turbine. For gas A, the ideal gas heat capacity is 30.0 + 0.02T, where the heat capacity is in J/mol-K and the temperature is in Kelvin. The equation of state for gas A has the following form: P(V-b) = RT + aP

Figure 4. Example homework assignment. Assignments from four years of classes are inventoried with hand-written solutions.

(s0 they are easier to grade, are of the appropriate length, and test the appropriate material) and preparing students to take exams are provided.[20,31]

- Suggested syllabus and schedule: This section includes pages with proposed schedules for 14-, 15-, and 16-week semesters, suggested grading scales, and possible course policies.

Each notebook contains a getting-started section that demonstrates how to download the course package (access through <www.cheme.com>), navigate through the materials, and use OneNote. Much of this information is demonstrated with screencasts. For example, the navigation screencast shows the instructor how to use the course notes for a specific day, including the instructor explanations that are included as part of the notes. One notebook section contains educational articles and website links[28,31] on active learning. Part of the first day of class is dedicated to showing students the motivation for using ConceptTests and peer instruction in class. Note that although the course package includes a large variety of tools that can be used in instruction, instructors are able to tailor the tools to their own style. For example, although the resources provided will be sufficient to institute a true flipped-classroom approach, instructors can personalize their notebooks to make only periodic use of active-learning techniques. We expect that instructors who are new to active-learning approaches may use a more modular approach as they gradually adopt new teaching practices.

USING ONE NOTE

Microsoft OneNote is a powerful software program that improves faculty efficiency by providing a means to organize a large amount of information. It is a component of Microsoft Office and consists of digital notebooks that are divided into sections, which are further divided into pages (and sub-pages). Text can be added to a OneNote page just like in a word processor, figures can be copied onto pages, files can be printed to them (or saved as icons that can be opened from the page), emails can be readily sent to them from Microsoft Outlook, handwritten text or figures can be added using a tablet PC, and links to other OneNote pages, to web pages, or to files, can be inserted. A page can be essentially any length. OneNote provides the following advantages that are important for the course package:

- It is easy to learn how to use.
- All text in the notebooks is searchable.
- Everything is continuously saved, and backup copies are created automatically.
- Moving between pages, sections, and notebooks is much faster than opening new Word, PowerPoint, or other files.
- Notebooks can be shared with others, and this can be much more efficient than email working with graduate students, teaching assistants, or staff. It provides an efficient method to delegate that is easy to follow up.
- Files are easily printed to OneNote; it shows up as a printer in the printer list.
A new project is easily started by creating a new OneNote page or section.

A OneNote page can be converted into a Word or PDF file or it can be directly emailed.

Files, programs, or websites that are used repeatedly can be opened by creating a link on a OneNote page. Opening a Word file that is used often is much faster from OneNote than searching through file folders and subfolders for the file.

It can be viewed on PCs, iPads, and phones and synced between them.

OneNote can be used to present material instead of PowerPoint in class; this mode of instruction is used by the developers of the package, where the OneNote page essentially provides an electronic “board” using a tablet computer to write notes in between prepared visuals. However, this mode of instruction is not required to use the course package. Content from OneNote can easily be copied to other applications such as PowerPoint.

INITIAL FEEDBACK

A beta version of the thermodynamics course package was used by a few faculty members in the fall of 2013. Feedback has been very positive. A new faculty member at another institution teaching thermodynamics for the first time stated: “I am so thankful that I had the thermo course package you developed. It certainly helped a lot!” Other faculty have expressed their appreciation for the materials to help them design their course. Further assessments to collect faculty suggestions and student feedback are being done to strengthen the course package. Interested faculty should request free access through the <www.learncheme.com> website under “Instructor Resources.”

ACKNOWLEDGMENTS

We gratefully acknowledge support from the National Science Foundation Grant DUE 1244183, which supported development of the course package, and Grant DUE 0920640, which supported development of the ConceptTests and screencasts used in this course package. We also thank Shell and the College of Engineering and Applied Sciences at the University of Colorado Boulder for financial support to prepare screencasts.

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REINFORCING CONCEPTS OF TRANSIENT HEAT CONDUCTION AND CONVECTION
With Simple Experiments and COMSOL Simulations

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Many engineering disciplines require heat transfer in their undergraduate curricula. Students are taught the concepts and mathematics of heat transfer in lecture courses, and this knowledge can be bolstered with hands-on experiential learning activities. It has been reported that more than a third of engineering students learn better with hands-on activities. In the literature, simple experimental systems have been developed to enhance teaching of heat transfer. Nassar, et al. utilized a flow chamber to calculate the convective heat transfer coefficient, and compared values with known empirical correlations. Clausen, et al. reported on free and forced convection for rectangular and spherical objects, and Smart augmented his lectures by heating up rectangular-shaped potato fries. In another study, small modules that fit on a student desk have been developed for students to study transient heat transfer. Some undergraduate chemical engineering laboratory courses offer experiments in heat transfer, but these can be unnecessarily complicated, and often do not have complementary computational modeling. In this paper, we propose a relatively simple module that can be performed as a classroom demo or as a laboratory experiment.

There are many articles in literature that propose computational methods for enhancing the teaching of heat transfer. Partial differential equations encountered in heat transfer problems have been numerically solved using simple tools such as spreadsheets or more elaborate programming with Matlab. Hossain, et al. measured the temperature profile of a metal fin, and compared the experimental values with numerical solution of partial differential equations and with computer simulations derived from commercially available ANSYS software. The study done in this paper was inspired by the work originally reported by Doughty and O’Halloran where they measured the transient temperature profile from metal and acrylic cylinders, and then performed finite element calculations using spreadsheets and Matlab programs. In a previous publication, Mendez, et al. presented results on a system similar to the one reported by Doughty and O’Halloran with the added novelty that user-friendly COMSOL Multiphysics was employed to perform three-dimensional (3-D) simulations.

To maintain a competitive edge in today’s global economy, chemical engineering students must be taught how to use the
latest technological tools. Since chemical engineering students typically are not trained to write elaborate computer programs, educators should elucidate the capabilities of commercial software that does not require extensive programming with languages such as Fortran or C++. The new trend followed by the software vendors is to sell applications that can handle so-called “multi-physics,” thereby giving the end user greater modeling capabilities. Since it has capabilities suited for the needs of chemical engineers, we introduce students to COMSOL Multiphysics by having them model transient heat transfer of some simple experimental systems. COMSOL has already been utilized by educators to simulate mass transfer,17 heat conduction in a fin,17 and hydrogen fuel cells.17 Mendez, et al. have demonstrated that COMSOL can effectively be used to model free-convection heat transfer from aluminum and plastic cylinders.11

In this article, we begin by describing the experimental and computational methods. We then compare the measured temperature versus time profiles of the solid cylinder and the liquid sphere with the profiles from COMSOL modeling. We also present results of student questionnaires that were used to assess the effectiveness of learning transient heat transfer by means of experimentation and computer simulations.

EXPERIMENTAL METHODS

Materials. Objects with cylindrical and spherical geometries were used. An aluminum alloy (7055) solid cylinder was used in the experiments (diameter = 0.0381 m, height = 0.130 m).11 The density (ρ), heat capacity (C), and thermal conductivity (k) of the aluminum are 2710 kg/m³, 1256 J/(kg · K), and 167 W/(m · K), respectively. For the sphere, water balloons were filled with 0 °C water to a diameter of 0.0365 m for free convection and 0.0476 m for forced convection. The properties of water are ρ = 998.2 kg/m³, C = 4183 J/(kg · K), and k = 0.598 W/(m · K). Figures 1 show photographs of the aluminum cylinder and water balloon. A hole was drilled from the top of the cylinder so that a thermocouple could be inserted to monitor the temperature at half the cylinder height. For the water balloon, the thermocouple was placed in the balloon’s opening and tied off using a rubber band.

Figures 1. Photographs of the aluminum (left) solid cylinder and the balloon filled with water (right). The thermocouples were inserted into the designated holes. The cylinder was placed on a thermally insulated Styrofoam surface, and the top was insulated with a Styrofoam disc.
Procedure. The cylinder was initially heated to an elevated temperature (~70 °C) in a lab oven. It was then removed from the oven and placed on a thermally insulated foam surface and a foam disk was used to insulate the top surface. A thermocouple was immediately inserted in the drilled hole and the temperature versus time profile was recorded until the solid cooled to ambient room temperature (~24 °C). Since the top and bottom surface were thermally insulated, the heat transferred radially from the cylinder to the cooler room-temperature air via convection. We studied both free convection and forced convection—the latter by blowing air across the cylinder with a fan (air velocity ~ 1 m/s). A similar procedure was employed for the water balloon except that it was initially cooled in a refrigerator to about 0 °C, and then set out in the lab to allow its temperature to rise. In this case, heat transferred from the ambient air via convection toward the center of the spherical water balloon.

COMPUTATIONAL METHODS

COMSOL Multiphysics version 4.2a was used to simulate the transfer of heat between the cylinder and sphere and the surrounding air. For the cylinder, we utilized a 3-D half cylinder since we assumed that heat conduction within the cylinder occurred entirely in the radial direction. Although the water balloon used was not completely spherical, we modeled it as a perfect sphere with COMSOL. The dimensions of the objects were drawn to match those of the actual objects. COMSOL employs finite element numerical methods to solve partial differential equations (PDEs). This software conveniently provides PDEs for various phenomena. We used the built-in “Transient Heat Transfer” module in which the software solves the PDE,

\[ \rho \cdot C_p \cdot \frac{\Delta T}{\Delta t} = \nabla \cdot (k \cdot \nabla T) + Q \] (1)

where Q is a convective heat flow flux term. This was accounted for with the following equation,

\[ Q = h \cdot (T_{\text{ext}} - T) \] (2)

where \( T_{\text{ext}} \) is the ambient room temperature, \( T \) is the temperature at the surface of the object, and \( h \) is the convective heat transfer coefficient. We employed the same method as Doughty, et al. to approximate the \( h \) from experimental measurements\(^{[11]}\) where they used

\[ \ln \left( \frac{T_{\text{c}} - T_{\text{ext}}}{T_{\text{i}} - T_{\text{ext}}} \right) = -\frac{t}{\tau} \] (3)

\( T_{\text{c}} \) is the transient center temperature (at \( r = 0 \)), and \( T_{\text{i}} \) is the initial temperature. \( \tau \) is

\[ \tau = \frac{\rho V C_p}{h A} \] (4)

where \( V \) and \( A \) are the volume and surface area, respectively. The experimental temperature data was plotted as a function of time, \( t \), according to Eq. (3), and a linear fit yielded an estimate of the heat transfer coefficient. To tune the COMSOL model, we adjusted the \( h \) value until the simulation results matched the experimental data. Since the COMSOL finite element software solves PDEs, the model required boundary conditions. As noted earlier, for the cylinder, we insulated the top and bottom surfaces with foam panels; therefore, we set such insulating boundary conditions in COMSOL. In addition, since we assumed that heat was transported only in the radial direction, we also applied an insulated boundary condition along the flat surface in the axial direction that split the cylinder in half. This same assumption led to the other boundary condition that there was zero heat flux at the centerline (\( r = 0 \)). Since the curved surface of the cylinder was exposed to ambient air, we specified this as the surface where there was convective heat transfer between the warm cylinder and the air. Likewise, for the spherical geometry, we assumed that there was zero heat flux at the center point, and also that the convective heat transfer occurred at the outer surface, which was exposed to ambient air. In addition, the default numerical solver and triangular mesh were used.

RESULTS

In Figure 2 (page 218), we present the experimental and computational results for the cooling of the aluminum cylinder with free and forced convection. For free convection, the temperature dropped slowly from 70 °C to room temperature near 25 °C over a period of about 4.5 hours. As expected, for forced convection, the temperature dropped rapidly from 70 °C to room temperature over a period of about 1.5 hours. These two sets of experimental data were used to estimate the \( h \) values that were found to be 10.1 and 47.9 W/(m²·K) for free and forced convection, respectively. The former value for free convection is in reasonable agreement with the \( h \) value reported by Doughty, et al.\(^{[11]}\) One of the goals of this teaching module was to have students become familiar with the COMSOL Multiphysics software to model this simple experimental system. The results from the 3-D COMSOL simulations are plotted in Figure 2. Within the COMSOL model, we used as a fit parameter the \( h \) values, and for the plots shown we found that 10.2 and 38.0 W/(m²·K) gave the best agreement. For both temperature profiles, there was excellent agreement between experiments and COMSOL indicating that the model is reasonably accurate.

In Figure 3 (page 219), we present the experimental and COMSOL results for warming up of the water balloon with free and forced convection. The experiments were run in a similar manner except the initial temperature of the water balloon was 0 °C. For free convection, the temperature rose slowly from 0 °C to room temperature over a span of 5 hours.
For forced convection, the temperature was elevated faster from 0 °C to room temperature in approximately 3 hours. From this experimental data the $h$ values for free and forced convection were estimated to be 7.4 and 16.6 W/(m$^2$·K), respectively. For the COMSOL model, we found the best agreement with $h$ values of 11.5 and 15.0 W/(m$^2$·K) for free and forced convection, respectively. Again, there is reasonable agreement between the experiment and the COMSOL Multiphysics simulations.

COMSOL simulations exhibit good agreement with experimental measurements. Modeling heat transfer with COMSOL Multiphysics has advantages that include user-friendly 3-D modeling, built-in PDE modules for heat transfer, and various tools to plot and visualize simulation results such as colored slice plots and video animations.

**ASSESSMENT OF STUDENT LEARNING**

In this work we report on a computational model that complements a simple experimental system. The objectives were to 1) enhance students' understanding of free and forced convective heat transfer, and 2) to provide them with an opportunity to learn how to use a modern computational tool. To assess if we met our objectives, students were asked to respond to a questionnaire. The undergraduate students were enrolled in the lecture course “Chemical Engineering (ChE) 420, Heat and Mass Transfer” and they performed this module while in the lab courses “ChE 440, Undergraduate Laboratory I” or “ChE 450, Undergraduate Laboratory II” in the Department of Chemical Engineering at California State University, Long Beach. The total number of students who filled out the questionnaires was 32, which is about 25% of the enrollment. The survey contained eight questions that were measured on a 5-point Likert scale with responses ranging from “Strongly Disagree” to “Strongly Agree” with scores from 1 to 5, respectively. Tabulated are the average scores along with the standard deviations.

As presented in Table 1, the questionnaire results indicate that students felt that lecture only was not sufficient for them to fully grasp the concepts of heat transfer. A large majority of those polled felt that the hands-on measurements were the most beneficial to their learning experience; however, they did have some reservations about conducting COMSOL simulations perhaps because they lacked prior knowledge about the software. Although students expressed a preference

![Figure 2. Temperature profile for aluminum cylinder at centerline radial position. Free and forced convection experimental data as symbols and COMSOL results as curves.](image)
to not perform the COMSOL simulations, they appreciated the educational value of this module as indicated by responses to questions 5-7. To reduce the added burden of learning how to use the COMSOL Multiphysics software in the future, we plan to introduce the software in lower-division courses, and to provide students with step-by-step custom instructions. We hope that this teaching module with a simple experimental system and complementary simulation can improve student learning about heat transfer with conduction and free and forced convection.

SUMMARY AND CONCLUSIONS

In this paper, we have reported on a teaching module that combines both experimental measurements and computational modeling of heat transfer phenomena. The experimental setup was relatively simple, and the procedure was easy to perform. COMSOL Multiphysics was employed to model heat conduction and convective cooling of an aluminum solid cylinder and liquid water inside.

<table>
<thead>
<tr>
<th>Questionnaire Statement</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. I already understood transient heat transfer based on lecture, textbook and homework, therefore, this module was not necessary.</td>
<td>2.7 ± 0.5</td>
</tr>
<tr>
<td>2. Conducting the experimental measurements was the most useful in helping me grasp the concept of transient heat transfer.</td>
<td>4.6 ± 0.5</td>
</tr>
<tr>
<td>3. Performing the COMSOL simulations was the most useful in helping me grasp the concept of transient heat transfer.</td>
<td>3.1 ± 1.1</td>
</tr>
<tr>
<td>4. Performing this module helped me grasp the concepts of conduction and convection.</td>
<td>3.5 ± 0.5</td>
</tr>
<tr>
<td>5. I prefer this type of combined experimental/computational module rather than only experiments.</td>
<td>2.5 ± 1.3</td>
</tr>
<tr>
<td>6. Seeing the in-class demo was sufficient for me to better understand transient heat transfer. The lab experiment was unnecessary.</td>
<td>2.9 ± 0.7</td>
</tr>
<tr>
<td>7. I would like for the faculty to develop such teaching modules for other chemical engineering courses/labs.</td>
<td>3.7 ± 1.0</td>
</tr>
<tr>
<td>8. I plan to learn more about COMSOL Multiphysics and try to perform simulations on my own.</td>
<td>2.4 ± 0.5</td>
</tr>
</tbody>
</table>

1=strongly disagree, 2=disagree, 3=no opinion, 4=agree, 5=strongly agree

Figure 3. Temperature profile for the water balloon at the center position. Free and forced convection experimental data as symbols and COMSOL results as curves.
a spherical-shaped rubber balloon. With the heat transfer coefficient estimated from the experimental data we found reasonable agreement between experiment and computer simulations. From the student questionnaire we found, overall, that students found value in this module, however, learning how to use the computer software require considerable effort. In the future, we hope to introduce students to the software in lower-division courses so that they can become comfortable and proficient in its usage.

ACKNOWLEDGMENTS

We thank Professor Larry Jang and Mr. Minh Tran for helping us with the experimental setup, and Ms. Sophia Nguyen for helping with the initial COMSOL modeling.

REFERENCES

INTEGRATING THE ChE CURRICULUM VIA A RECURRING LABORATORY

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Engineering education literature has found active learning to be beneficial. A review by Prince found support for collaborative learning, cooperative learning, and problem-based learning (PBL), all considered forms of active learning. Collaborative and cooperative learning refer to students working in groups toward a common goal, with cooperative learning further specifying that students are evaluated as individuals. PBL has several possible implementation schemes, but in general all types pose problems at the beginning of instruction and they tend to rely on self-directed learning by the students. Considering the evidence for the positive effects of active learning, many faculty have begun to adopt these teaching methods in the classroom. In a 2011 study of chemical engineering and electrical engineering faculty, 82.1% of the faculty members have used or are using one or more of the 12 Research Based Instructional Strategies (RBIS) as outlined by Borrego, et al. with 61% utilizing active learning. Although the response rate to the survey was low, it is qualitatively encouraging to see evidence of RBIS being implemented in the classroom.

In addition to classroom learning, laboratory experiences are a common practice in engineering education, and the benefits are well established. As noted by Sheppard, et al., a lab that coordinates theory and practice well can greatly support student learning. Further, labs may aid students who prefer a laboratory setting and view their learning differently than students who prefer classroom settings. While active learning is becoming more prevalent, many chemical engineering curricula (including the curriculum at City College of New York) traditionally focus on requisite courses before letting students engage with the material in the laboratory. Bordogna, et al. challenged this method by envisioning a more integrated curriculum. The traditional and integrated

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approaches are juxtaposed schematically in Figure 1. He argued specifically that the integrated approach would teach students to define problems, consider multiple solutions, and experience the emotional/intellectual aspects of confronting an open-ended problem with limited knowledge. With the aid of computers and simulations in particular, first-year engineering students could solve engineering problems before having the requisite knowledge in math and science. The integrated approach could also instill lifelong learning and incorporate the “Just-in-Time Teaching” (JiTT) approach. Benefits of JiTT include students showing higher improvement in pre/post assessments (Force Concept Inventory), increases in classroom attendance, and improved study habits. However, JiTT was the least known RBIS based on the survey of Reference 2.

Some programs have begun implementing an integrated curriculum. To confront the problem of segmented learning associated with the traditional approach, Clark, et al. developed a “spiral” curriculum for sophomore chemical engineers at Worcester Polytechnic Institute. Although not extended throughout the entire undergraduate experience, topics were revisited with increasing complexity throughout the term. The approach used open-ended design projects that incorporated cooperative learning and JiTT. When compared with students taught with the traditional approach, the spiral approach students had equal (or better) understanding of chemical engineering principles, better success in teams, higher satisfaction academically, and higher retention rates, and they performed better in subsequent courses. At Michigan

![Figure 1. a) The traditional undergraduate engineering curriculum and b) an integrated engineering curriculum (modified with permission from Wiley).](image-url)
Technological University, two integrated curriculum approaches were attempted. Instead of having a laboratory as a component of each course, a set of core labs was created that was separate from the courses but aligned with co-requisites. However, issues in implementation and keeping appropriate coordination between the lab and the concepts in the core course hampered this approach. A second approach was taken where the theoretical matter preceded the laboratory by one semester, which helped reinforce previously learned material. In the second-, third-, and fourth-year labs, the first lab of the term was a traditional experiment, and then subsequent experiments throughout the term were presented as a design challenge with a learning objective just beyond the students' current comprehension.

Recognizing the importance of active learning and laboratory experience, this paper focuses on the implementation of an integrated laboratory experience in chemical engineering at City College of New York (CCNY). CCNY is a recognized minority-serving institution with a college mission focused on serving a wide-range of student backgrounds. The laboratory is associated with the material and energy balance course, which typically enrolls approximately 50 students, and the experiments are based on using a Continuously Stirred Tank Reactor (CSTR). The students solve open-ended problems in groups, and the concepts are not only core to the material and energy balance course, they can be re-examined throughout the entire curriculum. This paper describes the goals, design, and implementation of this approach, survey data supporting the program, a path for integration into other courses, and analysis for future improvement.

DISCUSSION OF THE INTEGRATED CSTR PLATFORM

The discussion starts with motivation and goals of the lab at CCNY. Subsequently, the design and implementation are discussed with a focus on the CSTR construction and then application to a draining tank experiment. Continuity and integration to other parts of the curriculum are also discussed. Survey results are discussed, which show initial success in building community, teamwork, and understanding. Finally, the implementation over three terms is analyzed to suggest practical changes in the future.

Motivation for and goals of integrated lab

The motivation and rationale for this approach are a combination of the literature studies about engineering education previously discussed (knowledge-based) and surveys taken of our department during ABET accreditation (data-based). From a knowledge-based assessment, students benefit when qualitative physical understanding is complemented by quantitative analysis. The CSTR work facilitates such a synchronized approach, allowing students to move from a fact-based to an evidence-based approach toward science. Additionally, the lab platform can be viewed as a cognitive apprenticeship, allowing students with diverse backgrounds to more thoroughly engage in the discipline.

Three data-based surveys identified shortcomings in our chemical engineering educational plan at CCNY. The department's student survey revealed the biggest areas for improvement to be: "Academic facilities, e.g., laboratory" (3.4/5) and the "Student facilities at City College" (3.4/5). The CSTR platform addresses these shortcomings by bringing students into the lab in year 2 instead of year 4. The second survey was an average of three years examining the program outcomes defined by ABET. The three weakest areas (≤ 4.0/5) were: "Design and conduct experiments, and analyze and interpret data" (4.0/5), "Design a system, component, or a process to meet desired needs" (4.0/5), and "Identify, formulate, and solve chemical engineering problems" (3.9/5). The CSTR platform is predicated on open-ended problems that will allow the students to engage in all of those areas. The third survey asked questions to recent graduates (< 5 years) to rate various educational objectives against their satisfaction and perceived importance. These results are shown in Table 1. While the first two objectives are met, the second two objectives are not. A goal of the CSTR platform is to stress the importance of being able to solve open-ended problems and subsequently give students sufficient tools to address these problems.

Before the CSTR lab was introduced, the undergraduate chemical engineering curriculum at CCNY followed the traditional sequence noted by Bordogna, et al. However, Bordogna's proposed full curriculum integration can lead to difficulty in implementation: faculty may resist changes to established lecture formats, there may be the perception of accreditation issues, there may be a sense of too much change occurring too quickly, etc. Since laboratory-curriculum integration can be beneficial to the learning process, the

<p>| TABLE 1 |
| Survey results from recent alumni (&lt; 5 years) focusing on satisfaction and perceived importance of various educational objectives |</p>
<table>
<thead>
<tr>
<th>Educational Objective</th>
<th>Satisfaction</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ability to perform as design, process, and development engineers</td>
<td>4.10</td>
<td>0.98</td>
</tr>
<tr>
<td>Ability to pursue post-baccalaureate degrees</td>
<td>4.16</td>
<td>0.86</td>
</tr>
<tr>
<td>Ability to apply critical thinking to real-world problems</td>
<td>3.53</td>
<td>1.06</td>
</tr>
<tr>
<td>Ability to apply creativity and innovation</td>
<td>3.46</td>
<td>1.09</td>
</tr>
</tbody>
</table>
chemical engineering department was motivated to find a way to incorporate the integrated laboratory into the curriculum. The versatility of a CSTR laboratory platform allows for concepts covered throughout the undergraduate curriculum to be connected via a single laboratory setup, all without developing a new lab course or any changes to the overall prerequisite layout. Thus, fewer problems were encountered with implementation.

The integrated laboratory is designed to feature open-ended, design-oriented laboratory exercises centered on fundamental concepts as they are introduced. This integration gets students into a laboratory setting as soon as unit operations concepts are introduced in lecture. Also, immediate exposure to experiments and processes shows classroom learning is applied and realistic. Rather than just employing the lab as a tool to prove that lecture concepts can be observed and measured, the focus is on problem solving and design tasks grounded in lecture concepts. The goal is to develop engineering intuition, problem-solving skills, and an immediate sense of how lecture material is applied and useful. Furthermore, accomplishing this in a shared, practical laboratory framework develops clear connections between the various core classes, even as the complexity of the material covered builds.

**Design and implementation**

The Continuously Stirred Tank Reactor platform provides an ideal, flexible framework for chemical engineering design problems of increasing complexity. While clearly useful in the study of kinetics and reactor design, its applicability to earlier chemical engineering concepts merits discussion. At the start, mass and energy balances can be designed around the tank’s inlet and outlet ports. The key concept in play is simply "(Flow in) - (Flow Out) = (Accumulation)." Flow in can be controlled via stock solutions added either by hand or by a metered pump. Flow out corresponds to the tank effluent. Accumulation can be measured in several ways, with the simplest example being measuring the liquid depth inside. Thus, one can develop a model of the tank’s height as a function of time from a given initial height. "Designing" an initial tank height that will result in the tank draining to a given height after a set time becomes an open-ended exercise. Each exercise follows a set design schedule, shown in Figure 2.

The students choose the groups themselves, with a typical size between four and six members. In week 1, students configure their CSTR system to be useful in analyzing and designing toward a fundamental chemical engineering principle. In week 2, students are tasked with gathering enough data on the behavior of their system to be able to engineer its behavior for an unknown challenge during the final week. In week 3, students are given a single try to configure their CSTR system to produce a certain outcome pertaining to the design topic. Groups compete against each other with regard to the effectiveness of their solutions. This implementation scheme is also beneficial as it incorporates components of Kolb’s experiential learning theory. The complete implementation of the draining tank laboratory cycle is explained later in this section. Inspiration for various experiments came from Denn. A general schematic of our CSTR is shown in Figure 3. There are currently five CSTRs that we made ourselves from inexpensive pre-made materials (under $100 in terms of just the parts and ignoring labor).

The system is designed to be versatile, including modular components that can be easily disassembled and reconfigured. The outlet piping, mixer, and sensors are not fixed and can easily be exchanged for different pipe or tube diameters, blade configurations, and probes. This allows the setup to be useful in designing around and assessing a large array of variables taken from the complete chemical engineering curriculum. The students are further given design freedom in determining which sensors to use and ensuring what calibration, if any, needs to be done. The vessel body is made of acrylic and the
related piping ranges from 1/2" NPT to stopper-adapted, smaller-diameter tubings. Students have access to pressure, temperature, salinity, and pH probes, modular with regard to the USB SensorDAQ system (Vernier Software and Technology), as well as individual student-grade UV-VIS spectrophotometers (Ocean Optics). Over-the-side heaters are also available so temperature effects can be studied. Data is logged at a sampling frequency of the students’ choice using the LabVIEW software suite (National Instruments). While this equipment was used at CCNY, the choice of sensors and other peripheral equipment is general and easily customized to specific experiments, implementation schemes, and financial considerations.

A full laboratory cycle applied to the draining tank problem

The following sample exercise is taken from the material and energy balance course, held during the first semester of students’ sophomore year. The three weeks correspond to the stages shown in Figure 2.

Week 1

General Objective: Measure how pressure varies with changing liquid height

Do the following:

1) Set up tube half-filled with water, pressure sensor, and LabVIEW 2009/2010
   a) Open the program LabVIEW 2009/2010 to read detectors
   b) Click on “SensorDAQ Logger.vi”
   c) Hint: Press white play arrow followed by green play arrow
   d) Adjust the data collection frequency to 0.2 seconds/data point
   e) Do the axes make sense? Why or why not?
   f) Clean up after yourself when you are finished

2) Use output to determine how pressure changes as a function of height.
3) Plot “pressure vs. height” and fit/analyze data (at home).
   Note: You will need this plot for next week’s lab.

Week 2

General Objective: Measure how height changes with time (measuring pressure change)

Do the following:

4) Set up tank with water, pressure sensor, and LabVIEW 2009/2010
   a) Open the program LabVIEW 2009/2010 to read detectors
   b) Click on “SensorDAQ Logger.vi”
   c) Adjust the data collection frequency to an “appropriate” time scale
   d) Begin draining tank by opening valve
   e) Measure pressure change as a function of time
   f) Repeat this process two more times
   g) Clean up after yourself when you are finished (at home)

5) Use plot of pressure vs. height (from last lab) to make a plot of height vs. time
6) Fit first four points to $q_e = k$, $q_e = kh$, $q_e = kh^{1/2}$
7) Does the data agree or disagree with the class predictions

Week 3

General Objective: Use the information from the previous two labs to design a tank that drains to a height of 1 inch in exactly 1.5 minutes.

Do the following:

8) Calculate the volume of the tank (based on the area).
9) Based on previous two labs, estimate the initial volume that you need to have the tank drain to a height of 1 inch in EXACTLY one and a half minutes
10) Set up tank with the predicted volume (or height) of water
11) Drain the tank and measure how long it takes to reach the 1 inch mark

Note:

i) You cannot run a trial experiment of any sort. Your initial volume prediction must be based on calculations from the previous two weeks.

ii) After you open the tank, the clock will start, and you cannot touch the valve or tank.

iii) The teams with the times closest to 1.5 minutes will get bonus points on their lab reports.

Lab report
1) Each student must turn in her or his own report.

2) Follow the guidelines given to you in the first class (“Lab report guidelines” on Blackboard). Any deviation will lead to additional work by you and a lower grade.

3) Each report should be no longer than two pages. BE SUCCINCT.

4) The three paragraphs of the results/discussion sections should describe the following three topics:
   a) How do you relate pressure and height? Is this a linear relationship? Does it make sense?
   b) How does height change with time? Does it make sense? Why or why not?
   c) What calculations did you make to predict that the height would be 1” after 1.5 minutes?

5) References, raw data, and sample calculations are optional if you have room left after you complete the ABSTRACT, INTRODUCTION, EXPERIMENTAL, and RESULTS sections, which are mandatory.

The students choose their own teams for system design and data collection, although they are graded on individually prepared lab reports from the shared team data. The switch from group design and competitions to individual lab reports serves two purposes. First, by working as a group, students are engaged with each other in real discussions about the design problems. Since the equipment setups are minimally specified by the lab handouts, students are forced to debate among themselves the merits of various design choices. This, paired with the third week’s competition against other groups, keeps students engaged in active thinking about core concepts. Individual lab reports, by contrast, task students with developing a deep, individual understanding of the material covered, which is considered a cooperative active learning method. Further, as the lab report is submitted in the form of a short publication, scientific writing skills are developed and practiced on a continual basis.

Other laboratory experiments have been explored in this class. One laboratory investigated the mass balance of food coloring dye into the system via a step function concentration change in the feed. Another lab examined a two-step reaction scheme that progressed in terms of the system’s ammonia concentration [reacting ammonia and copper (II) sulfate]. Both of these experiments made use of the UV-Vis spectrophotometer. A third lab included an energy balance, measuring the power output of the heaters via temperature change. These general examples highlight the broad range of topics that can be studied via the CSTR. Note that while these topics are introduced in the second year, they become major topics studied in depth only later in the curriculum.

Integration into subsequent engineering courses
The organization of our chemical engineering curriculum in terms of prerequisites is shown in Figure 4a. The integrated CSTR platform provides a different way of viewing the same coursework progression, shown in Figure 4b. By studying and designing increasingly difficult chemical engineering challenges within the same apparatus, the way the various sub-disciplines work together and build on each other with regard to practical problems is constantly revisited and expanded. This building of structured complexity is obvious to students as they progress, rather than only accessible in retrospect, near graduation.

This integrated structure reflects the curriculum as it exists at CCNY. For instance, statistics is an important component of the lab, but the class appears outside of the boxed area in Figure 4b because our statistics course is currently taught in the mathematics department, making it harder to integrate features of the lab directly into an externally taught course. Importantly, this model is one example of implementing the vertical integration; different departments can apply this methodology to fit their own program (course layout, specific laboratory experiments, etc.).

Additionally, this approach highlights collaborative and cooperative learning where students benefit by building a sense of community within the department. To augment this sense of open collaboration, we have created an integrated lab space that can be accessed by the students for exploration and monitored by the faculty for safety beyond the prescribed lab hours. The space has an open design and includes experiments from our separations, unit operations, and introductory labs. This integration allows for the inclusion of the CSTR apparatus beyond the mass and energy balance class.

To that end, in the Fall 2013 semester, the CSTR lab framework was expanded to the chemical kinetics class, offered to seniors. These seniors were students who had previous experience with the CSTR lab framework from their sophomore year. A new exercise was given simultaneously to the seniors and current sophomores; neither group had done the exercise before. The work required designing a tank system to target a specified pH value at a given time by reacting a citric acid solution with sodium bicarbonate tablets. Mixing
rates and agitator configuration were left as open design variables, building tunable mass transfer resistance into the kinetic framework.

The task was to neutralize a pre-mixed citric acid solution to a near-neutral pH in four minutes. As the time delay was the key evaluation parameter, arriving at the neutralized state too quickly corresponded to a poor design. Prior to the design challenge, all groups were required to collect data correlating system pH to citric acid and bicarbonate tablet concentrations. They were also required to look at the evolution of the system pH during reaction under both strong and weak mixing conditions. Dissolution of the bicarbonate tablets is strongly influenced by mixing configuration. Dissolution times range from erratic tablet breakup in approximately 15 seconds using the most aggressive mixing to a gradual, metered dissolution over approximately 19 minutes using gentle mixing.

The sophomore class universally (10 out of 10 groups) approached the problem as a stoichiometric exercise. All 10 groups measured out a number of tablets that would bring the system to the desired pH when dissolved and reacted completely. They then set up their tanks with aggressive agitators and ran their neutralization designs with high mixing speeds. All groups had accurate calculations for predicting the final pH. Moreover, all groups had correctly observed the available range of mass transfer rates for which they could control. But none of the groups chose to use mass transfer as a controlling mechanism in their design. As a result, their target pH was sensible, but their timing was inaccurate, despite having collected high-quality design data. This outcome is not entirely unexpected, however. The sophomore class had not yet taken either mass transfer or chemical kinetics. As a result, the key concept would have to be inferred almost entirely from the new lab data.

By contrast, half of the senior class (five out of 10 groups) approached the problem using a mass transfer-limited design. Those groups measured out tablets containing bicarbonate in excess of the amount required to neutralize the system. They then chose mixing designs corresponding to the gentle, mass transfer-limited release rates. These five designs, using mass transfer as a tool, demonstrated much greater control of their systems, giving rise to clearly superior designs. The other five (strong mixing) designs were comparable to those of the sophomores. As the seniors had been trained in both mass transfer and chemical kinetics, their ability to better appreciate and design around mass transfer effects is both expected and desirable.

The difference in design choice and performance between seniors and sophomores during this experiment highlights that

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**Figure 4.** CCNY chemical engineering curriculum organizational models. a) The original case, without CSTR lab integration. An oval groups courses with a focus on hands-on, applied laboratory experience. Arrows show linkages between classes in terms of prerequisites. b) Vertical integration of courses via the CSTR lab framework. Arrows show classes linked via the design apparatus, where lab experience is now an integral part of all three years of the curriculum. The rounded box replaces the oval, showing a curriculum organized around problem solving and design experience. Prerequisites have not changed, but the rationale behind them is made clearer via escalating complexity of the lab experience.
the lab framework can and does scale with the students' class year. This does not necessarily mean there is sufficient data to say earlier laboratory exposure led to increased success, but it does show that the same framework is sufficiently flexible to be used throughout the curriculum to pair classroom learning with experiential learning. All groups were tasked with gathering comparable sets of pH, kinetic, and mass transfer data for their systems. But the seniors were able to recognize mass transfer effects as being the most powerful tool at their disposal. The sophomores, given the same initial data, were not yet at a point where they knew what to do with it. However, it is anticipated that the 10 “failed” sophomore attempts will lead to a better intuition about mass transfer when it comes time to learn the material as juniors.

Building on this example, we plan to continue to expand the CSTR lab framework into the other classes. Following the ideas of JiTT, small modular experiments will be developed to illustrate general concepts with students who are already familiar with the CSTR platform and the sensors available. The *raison d'être* for the chemical engineering curriculum can be opaque compared to other engineering disciplines, but this integration of a single system into the chemical engineering coursework provides an opportunity for students to see connections between the sub-disciplines.

**Results to date: enhanced understanding and community**

To directly quantify the benefits of the CSTR lab integration, a supplementary survey specifically about the new lab component was given to the department’s current senior and junior classes. Only students who had taken the introductory course with the CSTR lab component were asked to participate. The responses from the junior and senior classes are in Table 2 and Table 3, respectively.

In the junior class (33/34 responding), all questions were posed by asking students to rank a statement on a scale of 1-10, with 10 being “Strongly Agree” and 1 being “Strongly Disagree.”

The first two questions reveal that the CSTR lab acted as a powerful tool for enhancing a sense of community among our juniors. The remaining questions targeted the students’ feelings of how the labs helped them understand core engineering concepts. The responses to this section were also extremely positive, with students estimating that the lab’s impact on their sense of understanding was nearly as powerful as its impact on their sense of community as a class year.

**TABLE 2**

<table>
<thead>
<tr>
<th>Survey Question</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. if the CSTR lab integration helped “develop a sense of community with [their] chemical engineering class year”</td>
<td>8.8 +/- 1.4</td>
</tr>
<tr>
<td>2. if “working on the CSTR labs helped develop a sense of engineering teamwork”</td>
<td>9.0 +/- 1.6</td>
</tr>
<tr>
<td>3. if the lab framework “helped [them] better understand the concepts covered in the chemical engineering curriculum”</td>
<td>8.7 +/- 1.5</td>
</tr>
<tr>
<td>4. if the labs “helped [them] develop practical engineering insight into problem solving for real design challenges”</td>
<td>8.6 +/- 1.1</td>
</tr>
<tr>
<td>5. if the “CSTR labs helped [them] understand the chemical engineering curriculum by introducing topics like reaction design and transport concepts, starting in [their] sophomore year”</td>
<td>8.6 +/- 2.0</td>
</tr>
<tr>
<td>6. if the “introduction to junior- and senior-year concepts demonstrated by the CSTR labs gave [them] a stronger intuition of chemical engineering concepts”</td>
<td>8.3 +/- 2.1</td>
</tr>
</tbody>
</table>

**TABLE 3**

<table>
<thead>
<tr>
<th>Survey Question</th>
<th>% Strongly Agree and Agree</th>
<th>% Neither Agree nor Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. if the CSTR lab integration helped “develop a sense of community with [their] chemical engineering class year”</td>
<td>68</td>
<td>26</td>
</tr>
<tr>
<td>2. if “working on the CSTR labs “helped develop a sense of engineering teamwork”</td>
<td>89</td>
<td>9</td>
</tr>
<tr>
<td>3. if the lab framework “helped [them] better understand the concepts covered in the chemical engineering curriculum”</td>
<td>71</td>
<td>20</td>
</tr>
<tr>
<td>4. if the labs “helped [them] develop practical engineering insight into problem solving for real design challenges”</td>
<td>83</td>
<td>9</td>
</tr>
<tr>
<td>5. if the “CSTR labs helped [them] understand the chemical engineering curriculum by introducing topics like reaction design and transport concepts, starting in [their] sophomore year”</td>
<td>77</td>
<td>9</td>
</tr>
<tr>
<td>6. if the “introduction to junior- and senior-year concepts demonstrated by the CSTR labs gave [them] a stronger intuition of chemical engineering concepts”</td>
<td>69</td>
<td>22</td>
</tr>
</tbody>
</table>
The seniors (36/39 responding) completed similar surveys after they had finished the new CSTR exercise described in the section on construction and design of the platform. Scaling of the seniors’ data is different, as this class responded using the electronic course review system. Seniors selected for each question a response from a list of: “Strongly Agree,” “Agree,” “Neither Agree nor Disagree,” “Disagree,” or “Strongly Disagree.”

Thus, the seniors’ responses to the survey were also positive in terms of the students’ understanding and sense of community as a class year.

The seniors answered two additional questions about their experience. Reflecting the fact that the senior class was exposed to the most integrated form of the CSTR lab framework to date, we asked them if “Revisiting the 228 lab environment in 432 Chemical Reaction Engineering was useful in solidifying my understanding of reaction engineering and kinetics”: 47% answered “Agree” or “Strongly Agree” while 29% chose “Neither Agree nor Disagree.” This type of feedback will allow us to redesign the integration into this particular class to get even better results. We also asked if “[a] recurring lab framework throughout the curriculum would help [them] solidify [their] understanding of the chemical engineering concepts”: 83% answered either “Agree” or “Strongly Agree” while 14% chose “Neither Agree nor Disagree.” In that response, the seniors agree that expanding the lab to include still more classes is a trend in the right direction. One of the students’ open-ended feedback responses supported this theory nicely, stating: “[The CSTR] lab was one of the best labs, if not the best I’ve ever taken. I want more hands-on stuff in our coursework throughout the curriculum. Your work becomes tangible.”

**Synthesis of current results for improvement**

With each iteration of the lab, we have made several minor changes to both the logistics and content of the course. Based on the quality of the data, clarity of the lab reports, feedback from the students, and observations of the group interactions, we would like to highlight three major improvements that have facilitated student learning.

First, the open-ended cooperative learning environment is buttressed in the writing process, but students often need clear guidance in their technical writing. This does not mean that faculty or teaching assistants should provide any sort of remedial support. Rather, a clear set of guidelines, a well-defined example, high expectations, and rapid feedback all enable students to improve quickly.

Second, we found that it was important to calibrate clearly the students’ expectations for experimental success. Freshman labs in chemistry and physics are designed to lead students to a prescribed conclusion via a well-defined experimental apparatus. Therefore, students are often unaccustomed to learning through failure. To help remedy this issue, an initial lab was developed coaching students to understand the notion of benchmarking and being willing to quickly surrender their initial assumptions. The 2-hour benchmarking lab is based on Tom Wujec’s “Marshmellow Challenge.” In this challenge, teams of sophomores compete against each other to build the tallest free-standing structure possible out of fixed amounts of uncooked spaghetti, string, and/or tape. The marshmallow must remain on the top, and maximizing that height is surprisingly challenging.

Third, the initial labs were run effectively as in the standard once-a-week three-hour window, but we have learned that the development of a community around the notion of open-ended cooperative design requires time to adjust the initial experimental setup, reevaluate assumptions, and analyze the quality of data. Our initial lab schedule put students in the lab each week conducting setup, data collection, or competition, but reducing the number of experiments has allowed us to schedule in “team time.” This has also been facilitated by creating more accessible lab space where groups that were initially unsuccessful can explore new ideas.

Still, several changes are planned over the next semesters. Based on the described implementation for the last three terms, practical modifications moving forward include an enhanced role of programming in experimental setup and analysis, a module integrating control theory, and a systematic method to connect the CSTR apparatus to existing equipment in the unit operations laboratory.

**CONCLUSIONS**

A laboratory associated with the mass and energy balance course has been developed that allows for concept integration throughout the remaining curriculum. The laboratory is based on a CSTR that the students assemble and utilize to solve open-ended design problems. Each lab assignment is three weeks and ends with a design challenge based on understanding gained during the previous two weeks. This teamwork experience is complemented by each student writing a laboratory report (cooperative learning).

The knowledge gained in this sophomore-year class can be revisited throughout the curriculum in courses such as kinetics, transport, and controls. Benefits of this integration include earlier exposure to laboratory work, additional group work, and greater understanding of engineering concepts.

Qualitatively, this experience has been a success. The opportunity for students to work in groups toward a common goal across their undergraduate education has enhanced the sense of teamwork and community. Improvements to the lab have been made throughout implementation, and additional changes will be made to enhance the learning experience. This qualitative assessment has been bolstered by surveys of the students, giving initial quantitative support that the recurring CSTR platform is a success.
ACKNOWLEDGMENTS

We would like to thank the CCNY - Technology Grants for Teaching and Learning for funding the development of the CSTR platform. RST and MBK would like to thank NSF grant #1006407 for the support. Additional thanks are given to Professors Morton Denn and Jeffrey F. Morris and Dr. Pablo Bueno for their input in design.

REFERENCES

A MULTI-INSTITUTION STUDY OF STUDENT DEMOGRAPHICS AND OUTCOMES IN CHEMICAL ENGINEERING

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Studying the demographics and outcomes of Chemical Engineering (ChE) students provides valuable insight to the profession. Unlike many studies that aggregate all engineering majors, this work focuses on ChE. Chemical Engineering students have been shown to be different from other engineering students in terms of higher academic achievement on several academic performance criteria including high school grade point average (GPA), SAT math and verbal scores, time-to-graduation, and cumulative GPA. In a more recent study, Godwin and Potvin compared ChE students to other engineering students in terms of their career interests and attitudes. Using a sample of primarily first-year students, they found that ChE students were more likely to have taken higher-level chemistry in high school, had stronger desire to apply math and science in their careers, had a stronger interest in science and understanding the world, and had higher science identity. They did not find the differences in terms of academic achievement reported earlier and suggest some reasons due to differences in methodology, population, and time.

Around the world, ChE is known for having a relatively high fraction of women among engineering disciplines, but less work has been done to describe its racial and ethnic diversity. At a national level in the United States, the American Institute of Chemical Engineers (AIChE) recognizes the importance of promoting women and minorities in the profession through its Women’s Initiatives Committee (WIC) and Minority Affairs Committee (MAC) and its inclusion of “uphold and advance the profession’s standards, ethics, and diversity” in its mission statement. Since race/ethnicity and gender do affect experience, it is important to consider these factors. Most datasets are too small to permit disaggregation by both race/ethnicity and gender, let alone engineering discipline. However, the dataset used in this research permits disaggregation by all three factors. Thus, this work uses a critical race theory framework and considers the intersectionality of race/ethnicity and gender.

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MATTHEW W. OHLAND is professor of engineering education at Purdue University and a professorial research fellow in engineering education at Central Queensland University. He received the B.S. in engineering and the B.A. in religion from Swarthmore College, the M.S. in mechanical engineering and the M.S. in materials engineering from Rensselaer Polytechnic Institute, and the Ph.D. in civil engineering from the University of Florida. His teaching and research interests include the longitudinal study of engineering student development, peer evaluation, team formation, and high-engagement teaching methods. He is a fellow of the ASEE and the IEEE.

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RUSSELL A. LONG is director of Project Assessment in the School of Engineering Education at Purdue University. He received the B.M. in vocal performance from Augusta College, and the M.M. in vocal performance and the M.Ed. in student personnel services from the University of South Carolina. He manages MIDFIELD.

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For example, the pathways of Asian women and black men can be considered rather than the pathways of “women” or “underrepresented minorities.” In this paper, we highlight literature focused on ChE and then use a large dataset to conduct a multi-institution study of the demographics and outcomes for students in ChE disaggregated by race/ethnicity and gender. We also use a recently formulated “stickiness” metric—named from the concept of sticking with a major—to compare all students regardless of their matriculation pathway (first-time-in-college (FTIC) or transfer students).

Our work provides an unprecedented look at the demographics of ChE by race/ethnicity and gender. To the extent that the findings from the institutions studied here are representative of other institutions, those institutions can learn from our findings and can explore how their institutions address these common challenges. To the extent that institutional findings differ from those presented here, institutions may either be able to share promising practices with the larger community or identify opportunities for improvement.

BACKGROUND

In the aggregate, there is no gender gap in engineering persistence as shown in many studies. In a large multi-institution study that aggregated engineering majors, no gender gap in persistence or graduation was found for all races/ethnicities. Lord, et al. showed that there were gender differences in major selection within engineering. In a mixed-methods, multi-institutional study of the largest and most common engineering disciplines, Brawner, et al. found that ChE had the highest representation of women at matriculation (39%) and at the third semester (38%) of any engineering major in the study (some disciplines, such as biomedical engineering, have been shown to have higher representations but are not as common and were not included). In a single institution study with 2,474 men and 613 women majoring in engineering, Stine also found that 10% of those men and 23% of those women chose ChE. This is the highest percentage for women of any engineering major in that study. Six-year graduation rates in the major were high compared with other engineering majors: 48% for men and 49% for women for ChE while the aggregated overall graduation rate in major was 43% for men and 42% for women. Felder, et al. conducted a detailed study of ChE students’ experiences, finding that men and women in an experimental ChE course sequence had similar four-year retention rates. Men were more likely to drop out and lag in the curriculum. Women were more likely to switch to another major in good academic standing.

In one of the few studies to examine gender segregation critically across engineering majors, Litzler combined data from the Engineering Workforce Commission (EWC) and the Project to Assess Climate in Engineering (PACE) survey. The EWC data contains information from all U.S. schools of engineering, while the PACE data includes 21 large, public, research-intensive universities. For both the EWC and PACE data, ChE had higher representation of women than engineering as a whole. Only bioengineering and environmental engineering had higher representation, with industrial engineering and materials engineering equal. Litzler’s data show “clearly that there is a significant amount of variation at schools across the country in the proportion of women in chemical engineering.” She found that individual-level characteristics were more important than institutional variation in women’s major selection overall and particularly for ChE.

The extensive dataset used in this work allows for disaggregation by race/ethnicity, gender, discipline, and matriculation pathway to an extent never before attempted. Large national datasets such as IPEDS and that of the American Society for Engineering Education (ASEE) do not allow for this level of simultaneous disaggregation. Thus, the present study allows ChE faculty and administrators to learn about who enrolls and who succeeds in ChE in ways not possible using any other data source.

METHODS

MIDFIELD database and its demographics

This study uses the Multiple-Institution Database for Investigating Engineering Longitudinal Development (MIDFIELD), a dataset with 137,649 FTIC students matriculating in engineering and 39,354 transfer students articulating in engineering at 11 public, generally large U.S. institutions, nine of which are in the Southeast region of the United States. The demographics of the overall database are described in Reference 30. To define a ChE program, we use the Classification of Instructional Programs (CIP) code that is assigned by the institution to a degree program. Ten of the 11 MIDFIELD institutions offered ChE during the years studied. MIDFIELD includes four of the top 20 ChE degree-granting institutions in the United States by size. MIDFIELD is representative of the United States in terms of the representation of chemical among engineering disciplines and percentage of women in ChE. For the entire dataset, ChE graduates make up 9.8% of engineering bachelor degrees awarded at MIDFIELD institutions. The most recent national data available indicate that ChE comprised 8.4% of all engineering bachelor degrees awarded in the United States. Among women who received engineering bachelor degrees, 16.9% were in ChE in MIDFIELD while 14.7% were in ChE for national data.

It should be noted that there are potential limitations of the dataset. In particular, the participating institutions are mostly in the Southeast, which has different demographics than many other parts of the United States. Further, the participating institutions are all public and generally high-enrollment. While large public universities produce a majority of engineering graduates each year, the MIDFIELD data would not be expected to represent small, private engineering programs well.
The population studied in this work

Of the total MIDFIELD population, this work focuses on the 11,899 FTIC students and 2,370 transfer students who have a race/ethnic identity of Asian, black, Hispanic, or white; declared ChE as a major; and have sufficient data to calculate six-year graduation rates during the period from 1987-2010. We study students in multiple pathways: FTIC who matriculate directly into ChE or who choose ChE after completing a first-year engineering (FYE) program (where direct matriculation into specific engineering majors is not possible) (9,611 students); FTIC students who matriculate in other majors and switch into ChE (2,288); and transfer students who make their way into ChE (2,370). The group studied is representative of students in MIDFIELD in terms of race/ethnicity and is representative of students in ChE programs in the United States in terms of race/ethnicity—except for Hispanics, who are underrepresented (2.6% to 10.1%). The ChE group studied has a higher percentage of women when compared to the MIDFIELD engineering population (38% to 20%).[^2][^3]

ChE programs at MIDFIELD institutions awarded between 14 and 106 B.S. degrees in 2005, with a median program size of 50 graduates per year.[^1] This is consistent with the fact that MIDFIELD partners are larger and have a larger fraction of engineering enrollment than is typical.[^4] By comparison, the median number of graduates of ChE programs in 2005 at a U.S. institution (counting only institutions offering ChE) was 22.[^5]

Metrics used in this work

Several metrics are used in this analysis: the race/ethnicity-gender of those who start in these majors; trajectories of students; six-year graduation rates; and “major stickiness.” Of these metrics, stickiness requires elaboration. Major stickiness is the number of students who graduate in a major divided by the number of students who ever declared that major. Stickiness contains richer information than other persistence metrics; one of its critical benefits is its ability to pool data for students who enter engineering at different curricular points, including a large number who enter through first-year engineering programs.[^6] Students in FYE programs who are not permitted to enroll in a specific engineering major at matriculation are counted at the time they commit to a major in an administrative sense.

To facilitate the comparison of the pathways of ChE students at schools with FYE programs and schools where students matriculate directly to specific engineering majors, the Year 0 ChE enrollment at FYE schools is imputed by allocating the total FYE matriculated population to specific majors at enrollment in the same proportion as students chose each major after FYE. This assumes that the retention through the transition from FYE programs is the same for all engineering majors.[^32] Throughout this paper, the term “starters” refers to the total of FTIC students who matriculated directly in a major and those imputed to start in that major. “Transfers” refers to students who were designated as transfer students by the participating institutions. Transfer students are assigned as starting in a particular curricular semester, where for every 15 credits they transfer, their starting semester is increased by one.

In this paper, graduation is defined as having graduated by the sixth year from matriculation.[^27] We include the Year 4 outcome in addition to the Year 6 outcome because differences in graduation rate among students enrolled beyond the expected time-to-graduation have been observed when data are disaggregated by race/ethnicity and gender.[^3] Because MIDFIELD is whole population data, no sampling is involved. Consequently, differences are not compared in terms of statistical significance. Any differences between populations are real, although some may not be meaningful.

RESULTS AND ANALYSIS

Matriculants in ChE

1) Who starts in ChE?

Focusing on ChE starters, Table 1 shows the number of engineering (ENGR) starters in this dataset and the number choosing ChE disaggregated by race/ethnicity and gender. The percentages of engineering starters choosing ChE are shown in Figure 1. The vertical

![Figure 1. Starters choosing ChE.](image-url)

| TABLE 1 Demographic Distribution of Students Starting in ChE and Engineering |
|--------------------------------|------------------------------|-----------------|--------|
| Race/Ethnicity-Gender         | Starters in ENGR | Starters in ChE | % ChE |
| White Male                    | 58079            | 5011            | 9      |
| Black Male                    | 5943            | 524             | 9      |
| Asian Male                    | 4081            | 337             | 8      |
| Hispanic Male                 | 1922            | 132             | 7      |
| White Female                  | 13675           | 2530            | 18     |
| Black Female                  | 3523            | 773             | 22     |
| Asian Female                  | 1119            | 205             | 18     |
| Hispanic Female               | 531             | 99              | 19     |
| All Male                      | 70025           | 6004            | 9      |
| All Female                    | 18848           | 3607            | 19     |
| All Students                  | 88873           | 9611            | 11     |
reference line shows the 11% percent of all students choosing ChE. Data markers to the right of the aggregate values indicate populations choosing ChE at rates higher than average.

Women of all races/ethnicities are particularly attracted to ChE. Women of each racial group in engineering are dramatically more likely than men to start in ChE. For all races/ethnicities aggregated, women engineering starters are more than twice as likely to choose ChE as men (19% vs. 9%). This is consistent with the data reported by Stine. The largest gender gap in enrollment is seen for black students, and black women have the highest percentage (22%). Note that the preference of black women for ChE results in more black women starting in ChE than black men despite black men outnumbering black women in engineering overall.

2) Six-year graduation: How do ChE starters do?

Six-year graduation rate data for starters in ChE and for starters in a family of engineering disciplines (aerospace, bio, chemical, civil, computer, electrical, industrial, and mechanical engineering) are tabulated in Table 2 and graphed in Figure 2. The vertical hash marks indicate a population average: the percentage of a race/ethnicity-gender group starting and graduating within six years in the same discipline aggregated across a family of disciplines.

Regardless of race/ethnicity and gender, ChE starters graduate in ChE at rates comparable to or above their population average. Asian women are the most successful with the highest graduation rate and largest difference from their population average for engineering overall. Asian and black students and white men in ChE are also noticeably above their population averages. Hispanic men graduate in ChE at rates slightly better than in other specific engineering disciplines while white and Hispanic women in ChE are slightly below. Even so, Asian students, particularly women, are notably successful in ChE. Except for the Asian students, these graduation rates are lower than those reported by Stine for a single-institution study with all races aggregated.

Combining all engineering disciplines, research has shown that women of all races/ethnicities graduate at comparable or higher rates to men. This finding holds for ChE by itself. Asian, black, and Hispanic women graduate at higher rates than their male counterparts. White men and women have almost identical graduation rates with men slightly higher (40.9% vs. 39.8%).

Trajectory of ChE student enrollment

The graduation rates of starters ignore students who start in other majors or other institutions—who constitute a noticeable fraction of graduates. Specifically, transfer students and students starting in majors other than engineering (most commonly in an undecided pathway) make up 31% of ChE graduates (and fractions ranging from 27% to 66% for other engineering majors). Students who start in other engineering majors and graduate in ChE also add to that number. Focusing on completion statistics also ignores the path students take, such as when students enter and leave a major.

Figure 3 is a collection of time-series plots showing the number of students enrolled in ChE at matriculation (year 0), 4 years later, and 6 years later, disaggregated by race/ethnicity and gender. The vertical scale (numbers of students) is logarithmic in base 2. The horizontal scale (years from matriculation) is linear.

| TABLE 2 | Distribution of ChE Starters Graduating in ChE in 6 Years |
|---|---|---|---|---|---|---|
| Race Ethnicity-Gender | Starters | Six-yr grad | Rate(%) | Starters | Six-yr grad | Rate(%) |
| Asian Female | 205 | 99 | 48 | 871 | 356 | 41 |
| Black Female | 773 | 298 | 39 | 2989 | 1063 | 36 |
| Hispanic Female | 99 | 37 | 37 | 422 | 161 | 38 |
| White Female | 2530 | 1007 | 40 | 10526 | 4235 | 40 |
| Asian Male | 337 | 148 | 44 | 3409 | 1407 | 41 |
| Black Male | 524 | 176 | 34 | 5187 | 1560 | 30 |
| Hispanic Male | 132 | 45 | 34 | 1546 | 508 | 33 |
| White Male | 5011 | 2051 | 41 | 47852 | 18048 | 38 |
While many starters leave, others take their place. Large losses are seen for all starters. The shallower slopes of the “all” curves show that students of each population are entering the major, compensating for starters who are leaving. In fact, in ChE, more Asian students graduate than start due primarily to the influx of students into the major.

Trajectories in ChE differ by race/ethnicity but not gender. From matriculation until Year 4, starters’ trajectories have similar slopes for all racial/ethnic groups. Between Years 4 and 6, however, there are steeper negative slopes (indicating higher percentage losses) for black and Hispanic students compared with white and Asian students. As stated earlier, ChE gains Asian students from matriculation to graduation. The influx of Hispanic males results in more students at Year 4 than matriculation but those gains diminish by Year 6. Black students have the steepest slopes indicating the highest percentage losses. Cross-sectional studies, which calculate graduation rates by dividing the number of students graduating by the number who were enrolled six years earlier, mask the striking losses of matriculants. For example, ChE graduates about as many Asian males as it enrolls initially, which would be calculated as a 100% retention rate if we simply compare graduates to starters. This hides the true behavior—that half of the starters are gone and have been replaced with other students: transfers and students from other majors. Interestingly, the trajectories for each racial/ethnic group are similar for female and male students, so trajectories in ChE do not appear to differ by gender to the extent that has been found for other engineering disciplines. Even comparing the trajectories of all female and all male Hispanic students, where the difference is noticeable, the difference is smaller than has been observed for other engineering disciplines.13

Stickiness of students in ChE

The presentation of trajectories in the previous section is useful and disaggregates student pathways, but is also complex, requiring 16 trajectories with three data points each to describe the enrollment and graduation behavior of the various populations. Here, then, it is useful to employ another metric that can pool students coming from different pathways. As noted earlier, the major stickiness is the number of students who graduate in a major divided by the number of students who ever declared that major, regardless of the path by which students enter the major. These data are tabulated in Table 3 and graphed in Figure 4 (page 236) where the vertical reference line indicates the aggregate stickiness for all students in ChE.

Asian females have a surprisingly high stickiness in ChE, with Asian males, white students, and Hispanic females trailing by approximately 8% at the aggregate value. Women were found to have higher stickiness than their male counterparts for each race/ethnicity in EE and ME.1213 This is true for Asian, black, and Hispanic women in ChE. White women, however, are slightly less likely to stick in ChE than their male counterparts (52% vs. 53%). Black students and Hispanic men
TABLE 4

Stickiness of FTIC and Transfer Students in ChE

<table>
<thead>
<tr>
<th>Race/Ethnicity-Gender</th>
<th>FTIC</th>
<th>Transfers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grad in ChE</td>
<td>Ever in ChE</td>
</tr>
<tr>
<td>Asian Female</td>
<td>174</td>
<td>285</td>
</tr>
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<tr>
<td>White Female</td>
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<tr>
<td>Asian Male</td>
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<td>467</td>
</tr>
<tr>
<td>Black Male</td>
<td>213</td>
<td>573</td>
</tr>
<tr>
<td>Hispanic Male</td>
<td>80</td>
<td>180</td>
</tr>
<tr>
<td>White Male</td>
<td>2770</td>
<td>5286</td>
</tr>
</tbody>
</table>

**Figure 4. Stickiness in ChE.**

The overall stickiness behavior for transfer students in ChE is similar to that of starters, with women having higher stickiness overall and black students and Hispanic males having lowest stickiness. White male and female starters have almost identical stickiness while white male transfers have slightly higher stickiness than white female transfers. Female transfer students of all race/ethnicities except white are more likely to “stick” with ChE than their male counterparts. Hispanic female transfers are the most successful of all populations studied here (71.1%). This is in marked contrast to their stickiness as starters. Asian female transfers do only slightly better than Asian male transfers.

Consistent with earlier work,[13] transfer students tend to be more sticky than FTIC students. This is likely related to their having already successfully passed some engineering prerequisites and thus being more strongly committed to the major before entering our database. Asian women in ChE are unique in that FTIC have higher stickiness than transfers. This unexpected behavior could be related to the very high stickiness of FTIC Asian women and suggests the need for qualitative work in this area.

**DISCUSSION**

These results are intended to inform faculty about the students in the ChE classroom and the relative success of different populations. Department heads can benefit from this information by learning about which populations are underrepresented in ChE as well as which may need more support to be successful. Deans who must balance the performance and needs of all engineering disciplines can benefit from learning about the particular challenges that each discipline faces in recruiting and graduation. For example, the attractiveness of ChE to women may inform recruiting efforts that attract more women to other engineering disciplines. ChE department heads can compare their demographics and outcomes to those described here as a detailed baseline.
The overall success of students in ChE might be linked to their reported better academic preparation than other engineering students (high school GPA, SAT math and verbal).\textsuperscript{[55]} The research presented here adds depth to the description of this success by showing the variation by race/ethnicity and gender.

The higher percentage of women in ChE compared to other engineering disciplines is supported by our work and consistent with earlier studies that showed that, with race/ethnicity aggregated, ChE attracts a higher fraction of women than other majors.\textsuperscript{[5,7]} We showed that this behavior begins at matriculation. This is in stark contrast to findings for electrical and mechanical engineering, which consistently attract women at much lower rates than their representation in engineering as a whole.\textsuperscript{[1,2]}

This suggests that ChE is doing something right when it comes to recruiting women that other disciplines could learn from.

Godfrey asserts that, compared to other engineering disciplines, ChE has a less “macho” culture, which created “an environment in which women were treated as individuals, rather than generalized as a group.”\textsuperscript{[10]} She also suggests that women might be drawn to ChE because “a reliance on prior practical knowledge or tinkering experience did not seem as essential.” Previous qualitative work showed that motivations for women choosing ChE included flexibility and career opportunity.\textsuperscript{[24]}

Findings by Godwin and Potvin may provide the best explanation of why ChE attracts a higher fraction of female students, although their research on student motivation of ChE students did not disaggregate by gender.\textsuperscript{[10]} They found that ChE students were more likely than other engineering students to want to address energy (60% vs. 47%), disease (39% vs. 18%), climate change (20% vs. 11%), and water supply (34% vs. 19%) in their future careers.\textsuperscript{[6, p.140]} These opportunities are consistent with the messaging recommended by the National Academy of Engineering’s Changing the Conversation\textsuperscript{[33]} and subsequent Messaging for Engineering.\textsuperscript{[34]}

Thus, some of the messages that ChE has been communicating (through recruiting materials, websites, etc.) fit well with messages shown to be attractive to women engineering students. As more is understood about the climate for women in ChE, educators might benefit from the work of Hoh, who developed an activity that highlights prominent women in ChE to break down stereotypes and raise awareness of women’s contributions to the field.\textsuperscript{[35]} Whereas these earlier findings are helpful in understanding why ChE attracts a higher fraction of women, more qualitative research is needed to explore the reasons why women persist in ChE at higher rates than men.

The particular success of Asian women in ChE is interesting. Our findings of high graduation rates for Asian men and women are consistent with literature showing that Asian students have the highest rates of matriculation and persistence in engineering and science of all racial/ethnic groups\textsuperscript{[36–38]} and that the interest in engineering and science careers starts as early as eighth grade.\textsuperscript{[39]} The model minority stereotype may also play a role in Asian students choosing engineering and ChE.\textsuperscript{[40]}

Because Asian-American students are assumed to be good at math and science, they may be encouraged to pursue careers such as engineering by their families, teachers, and guidance counselors. For Asian-American women, this may counteract some of the negative messages about engineering as a fit for women. Our findings of high graduation rates for Asian ChE students also resonates with work by Marra, Rodgers, Shen, and Bogue where Asian students were the only racial/ethnic group to see a slight increase in reported feelings of inclusion after a year of engineering study.\textsuperscript{[41]}

None of this literature disaggregates by both race/ethnicity and gender to consider the unique experiences of Asian women. Such work would help in understanding our quantitative results.

While challenges exist for black students, this has been found for other disciplines as well.\textsuperscript{[30,32]} There is evidence that this is less a racial/ethnic effect and more a socioeconomic effect, noting that black students in MIDFIELD are more likely to come from low-socioeconomic-status high schools.\textsuperscript{[24]}

In ChE, Hispanic female transfers have the highest stickiness of all populations studied (71.1%). Hispanic women transfer students were also found to have higher stickiness in EE (68%), ME (62.5%),\textsuperscript{[32]} and engineering overall.\textsuperscript{[43]}

This suggests that the success of the transfer pathway for Hispanic females is not a disciplinary effect.

CONCLUSION

Using a large, multi-institutional dataset, we show that trajectories for ChE students differ by race/ethnicity. Chemical Engineering is different from other engineering disciplines in that trajectories do not differ by gender to the extent observed in engineering in the aggregate and in other specific disciplines. In this dataset, men outnumber women in ChE except among black students. While ChE starters graduate in ChE at rates comparable to or above their racial/ethnic population average for engineering, women choose and graduate in ChE at similar or higher rates than men of the same race/ethnicity. Typical of other engineering disciplines, external transfers and internal switchers replace starters who leave. Transfer students are generally more successful than starters. However, Asian women who start in ChE graduate at a higher rate than other populations and are more successful than Asian women transfers. These findings highlight the need to disaggregate by race/ethnicity and gender to expose intersectional effects.

ACKNOWLEDGMENT

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11. <http://www.aiche.org/community/committees>


EXPERIMENTS IN PHARMACEUTICAL ENGINEERING FOR INTRODUCTORY COURSES

ALEXANDER V. STRUCK JANNINI, C. STEWART SLATER, AND MARIANO J. SAVELSKI
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The year of 2010 marked one of the highest points of the pharmaceutical industry, where it had the second largest earnings of all industries. The pharmaceutical industry also increased its worldwide profit growth of 4.2% to approximately 800 billion USD that year. This is substantial growth, considering that in the year 2007, the pharmaceutical industry amassed revenue of 315 billion USD. These economic factors are coupled with shifting paradigms of the industry, such as a move toward shorter drug development times and an increased openness to change existing processes, which will increase the need for chemical engineers with pharmaceutical training. In 2010, 5% of employed chemical engineers and 14% of all biomedical engineers in the United States worked in pharmaceutical and medicinal manufacturing. From 2004 to 2014, roughly 76 thousand jobs are to be created in the pharmaceutical and medicine manufacturing sector, while basic chemical manufacturing jobs are to decrease by roughly 46 thousand in that same timespan.

As the demand for engineers has increased in the pharmaceutical industry, universities have found a need to provide engineers with education in the field of pharmaceutical engineering. Pharmaceutical engineering is defined as the design of pharmaceutical and diagnostic products and the associated manufacturing processes. Several universities have incorporated pharmaceutical engineering education into advanced degree studies. Some examples of universities that have introduced pharmaceutical engineering programs on the graduate level are Rutgers University, the University of Michigan, and the New Jersey Institute of Technology. All three of these universities offer a master’s degree program...
in pharmaceutical engineering, while Rutgers University also offers a pharmaceutical engineering option for Ph.D. students in chemical and biochemical engineering. This pharmaceutical engineering option requires five courses that focus on the different aspects of pharmaceutical engineering.\(^9\)

Stevens Institute of Technology offers a master's degree program in pharmaceutical manufacturing. The goal of this program is to provide students with a strong background in Good Manufacturing Practices, project management, and pharmaceutical facilities. This is considered an interdisciplinary program, administered by the mechanical engineering department.\(^10\) In addition, Purdue University offers graduate scholarships from the Department of Education's Graduate Assistance in Areas of National Need program for students to continue research in the field of pharmaceutical engineering. These graduate students also have the ability to be part of an international exchange program, gain industry experience through internship opportunities, and conduct supervised teaching to prepare them for a career in academia.\(^11\) Due to the expanding interest in pharmaceutical engineering training, the National Science Foundation funded an Engineering Virtual Organization to facilitate the creation and sharing of pharmaceutical engineering educational information.\(^12\) From this funding, the website <www.PharmaHUB.org> was created, and is now used to compile and share pharmaceutical engineering research, technology, and educational resources.

With this increased interest in pharmaceutical engineering at the graduate level, there has been some diffusion into undergraduate curricula. A majority of the universities that have developed undergraduate pharmaceutical engineering programs are found in Europe. In 2003, the University of Basel, in Switzerland, introduced a bachelor's program in pharmaceutical engineering.\(^13\) For the most part, however, colleges and universities tend to offer pharmaceutical specializations within traditional bachelor's degree programs. This is especially true in the engineering colleges of the United Kingdom and Scandinavia. In these countries, the pharmaceutical industry is a major contributor to the country's economy. For example, 40 percent of all exports from the Republic of Ireland are pharmaceuticals.\(^14\) In the United States, the University of Iowa offers a pharmaceutical specialization for undergraduates. This specialization can be obtained through higher-level electives that focus on different aspects of pharmaceutical sciences, such as drug delivery systems and basic pharmacology.\(^15\) Stevens Institute of Technology also offers a pharmaceutical manufacturing concentration for students of mechanical engineering. This specialization is obtained through courses that incorporate pharmaceutical facility design, validation, and hands-on projects in the field of pharmaceutical manufacturing.\(^16\)

Within these specializations, a majority of emphasis is on upper-level undergraduate courses, such as creating special topic courses that focus on pharmaceutical sciences. At the New Jersey Institute of Technology, a class focusing on drug transport and pharmacokinetics was implemented as a specialty topic course for students wishing to obtain a specialization in pharmaceutical engineering.\(^17\) The Georgia Institute of Technology has a course for senior and graduate-level students in the field of pharmaceutical engineering; specifically drug design, development, and delivery.\(^18\) Rutgers University has a Pharmaceutical Engineering Training Program, which allows both graduates and undergraduates to work on projects based on realistic problems found in the pharmaceutical industry. These projects deal mainly with product manufacturing or process research and development.\(^19\)

Although new upper-level elective courses can be developed to include pharmaceutical engineering concepts with relative ease, there is a level of difficulty when trying to incorporate concepts into lower-level undergraduate courses. In particular, the concepts have to be appropriate for students who are just beginning their undergraduate study. In addition, these concepts might have to be presented in ways that can be applicable to different engineering majors. There is also the complexity of adding new courses into an already saturated curriculum.

One approach is to modify existing courses so that they have a focus in pharmaceutical engineering and at the same time, meet student learning outcomes. For example, problem sets developed at Rowan University for use in lower-level undergraduate courses contain material and energy balances that incorporate different aspects of pharmaceutical engineering.\(^20,21\) In addition to using problem sets, incorporating pharmaceutical concepts into laboratory experiments can be used to reinforce the course's existing educational objectives. One of the initial efforts in this was the development of a first-year laboratory experiment that focused on an investigation of the controlled release principles of drug delivery methods through the dissolution of a lozenge.\(^22\)

This paper presents synopses of several experiments that have been developed for use in a lower-level, laboratory-based course. These experiments were designed to not only introduce pharmaceutical concepts, but also to reinforce basic engineering educational objectives such as: understand and apply core science and mathematics principles; work individually and in teams to identify and solve engineering problems; and design and conduct experiments as well as analyze and interpret data.\(^23\) The experiments discussed in this paper will be grouped by the pharmaceutical engineering concept that they encompass; either pharmaceutical fundamentals, drug manufacturing, drug formulation/delivery, or pharmacokinetics/pharmacodynamics. These experiments can also be used in tandem with course materials developed by others to further reinforce pharmaceutical concepts. The problem sets that were developed by Rowan University,\(^20,21,24,25\) and other supplemental course materials available from PharmaHUB\(^26,27\) may be used to provide more detail about topics—such as the regulatory issues, quality control, experi-

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### Table 1

<table>
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<td><strong>Variance</strong></td>
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<td><strong>1.52 · 10^{-5}</strong></td>
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</table>

The experiments were designed to meet the safety standards of a typical undergraduate laboratory and be performed by the students in approximately 2 hours. The cost of these experiments was also considered, so they do not rely on highly specialized equipment and the operating costs are reasonable, allowing the laboratory experiments to be relatively inexpensive in comparison to other chemical and biochemical unit operations. Another point considered when developing these experiments was the ease of the setup.

Two versions of these experiments are available; a student version and an instructor version, both of which can be found on the website <www.PharmaHUB.org>. The PharmaHUB homepage has a Resources section on the left-hand side of the screen, where the tag “Experiments” will automatically direct the user to all the laboratory experiments available. The Teaching Materials quick link can also be used from the PharmaHUB home page. This will bring the user to a screen listing all of the teaching materials available. The user can then find the appropriate lab from the alphabetical listing of educational resources or use the “Experiments” tag to find them.

This paper only includes representative experiments; others are available on the website. The pharmaceutical and engineering concepts that the experiment would incorporate are discussed in a brief introduction, which the students would read before beginning the experiment. The instructor’s version includes more detailed procedure, equipment and supplies lists, additional pictures and/or diagrams of correct setups for the laboratory experiments, concepts to reinforce, and a solutions section. To obtain access to the instructor versions, faculty must register to the PharmaHUB website. Currently, the experiments that can be found on PharmaHUB are the following: Tablet Statistical Analysis Lab; Asthma Drug Delivery Lab; Antacid Comparison Lab; Effervescence Reaction Lab; Fluidization of Pharmaceutical Substances Lab; Degradation of Dissolvable Strips Lab; Bandage Comparison Lab; and Creation of Dissolvable Strips Lab.

### Experiments Developed

**Pharmaceutical fundamentals**

One of the introductory laboratory experiments created to acquaint students with the fundamentals of the pharmaceutical industry is the Tablet Statistical Analysis Lab. The objective of this experiment is to conduct a statistical analysis on the mass of analgesics; in this case, ibuprofen tablets. From an educational perspective, the intended outcome of the experiment is that the students will gain experience interpreting data and using some basic statistical analysis methods. Statistics is an important aspect of the pharmaceutical industry, used to determine the reliability and accuracy of data taken from drug samples, monitor and detect the adversities of a process, and assess the capability and reliability of a process.[28]

For this experiment, students take mass measurement of two types of ibuprofen tablets; Advil® brand and a generic store brand. Table 1 shows example raw data of these mass measurements. Students are given 10 samples of each brand, and then take mass measurements using an analytical scale. The first calculations performed are mean (\( \bar{x} \)), standard deviation (\( \sigma \)), and variance (\( \text{var} \)) of both brands. Students then determine if the masses of the two brands are significantly different from each other through an F-test. The equation for the F-test, along with the calculations used based on the raw data, is shown as Eq. (1).

\[
F_{\text{exp}} = \frac{s_1^2}{s_2^2} = \frac{(9.726 \cdot 10^{-5})^2}{(1.526 \cdot 10^{-5})^2} = 40.63 \tag{1}
\]

For this experiment, the F-critical value was given as 3.18, based on the F-critical value table found in the Montgomery, Runger, and Hubele statistics text.[29] Since the experimental F-value is greater than the critical F-value, the two brands are considered statistically different. A t-test is then used to compare the two sets of data to a known mass of an ibuprofen tablet (\( \mu_0 \)), obtained from the Handbook of Pharmaceutical Manufacturing Formulations.[30] The t-test equation, along with a sample calculation of the t-test for the generic brand, is shown in Eq. 2.

\[
t_{\text{exp}} = \frac{\bar{x} - \mu_0}{\frac{\sigma}{\sqrt{n}}} = \frac{0.3320 - 0.4800}{0.00391/\sqrt{10}} = 119.8 \tag{2}
\]

The critical t-value, or t-critical, was determined to be 2.262.
using a generic t-table in the Montgomery, Runger, and Hubele text. Since the experimental t-value was larger than the t-critical value, it can be concluded that the generic store brand is statistically different than the theoretical value. When the t-test is conducted for the name brand, it was found that experimental t-value was smaller than the critical t-value. This leads to the conclusion that the name brand was not statistically different than the theoretical value. The calculation for this is shown in Eq. (3).

\[
t_{\text{exp}} = \frac{\bar{x} - \mu_0}{\sigma / \sqrt{n}} = -1.50986 / \sqrt{10} = 2.136
\]  

(3)

From these calculations, students can see that there is a difference between the two brands. In fact, the data shows that the standard deviation for the generic brand was lower than the name brand. The reason is that the generic brand did not have a sugar coating or a polishing coat like the Advil® brand. These coatings are much less regulated than the active pharmaceutical ingredient (API) content of the tablet, and as such, add more variance to the population. The students also see that the generic brand does not correlate well with the literature value, which is also due to the lack of coatings. As such, the values may change depending on the generic brand used for this experiment. Students also perform an outlier test, taking a portion of their data analysis for a box-and-whisker plot to determine any outliers. Students should not find any outliers in their experimental data, since the tablets are subjected to the high standards of pharmaceutical manufacturing. Students also complete an exercise where they are given a table of mass measurements from a hypothetical batch of tablets, and must determine whether or not an outlier exists (Table 2).

<table>
<thead>
<tr>
<th>Data Provided</th>
<th>Sorted Data (Low → High)</th>
<th>Quartiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4850</td>
<td>0.4217</td>
<td>Q1 0.4665</td>
</tr>
<tr>
<td>0.5198</td>
<td>0.4448</td>
<td></td>
</tr>
<tr>
<td>0.5048</td>
<td>0.4465</td>
<td></td>
</tr>
<tr>
<td>0.4857</td>
<td>0.4481</td>
<td></td>
</tr>
<tr>
<td>0.4786</td>
<td>0.4662</td>
<td></td>
</tr>
<tr>
<td>0.5435</td>
<td>0.4668</td>
<td></td>
</tr>
<tr>
<td>0.4448</td>
<td>0.4686</td>
<td></td>
</tr>
<tr>
<td>0.4668</td>
<td>0.4786</td>
<td></td>
</tr>
<tr>
<td>0.4465</td>
<td>0.4835</td>
<td></td>
</tr>
<tr>
<td>0.4835</td>
<td>0.4837</td>
<td></td>
</tr>
<tr>
<td>0.4686</td>
<td>0.4850</td>
<td></td>
</tr>
<tr>
<td>0.5211</td>
<td>0.4857</td>
<td></td>
</tr>
<tr>
<td>0.4863</td>
<td>0.4863</td>
<td></td>
</tr>
<tr>
<td>0.4217</td>
<td>0.5048</td>
<td></td>
</tr>
<tr>
<td>0.4481</td>
<td>0.5101</td>
<td></td>
</tr>
<tr>
<td>0.4837</td>
<td>0.5198</td>
<td></td>
</tr>
<tr>
<td>0.5895</td>
<td>0.5211</td>
<td></td>
</tr>
<tr>
<td>0.5227</td>
<td>0.5227</td>
<td></td>
</tr>
<tr>
<td>0.4662</td>
<td>0.5435</td>
<td></td>
</tr>
<tr>
<td>0.5101</td>
<td>0.5895</td>
<td></td>
</tr>
</tbody>
</table>

A box-and-whisker plot can then be used to show the outliers (Figure 1).

As an introductory experiment, this lab presents important pharmaceutical terminology. Students learn about the different pharmaceutical substances, such as API and the different types of excipients (fillers, binders, glidants, etc.). These technical terms are reinforced through an exercise where students determine the API and look up the first three inactive ingredients or excipients and their functions. In addition, students learn about batch manufacturing processes and receive an introduction to process flow diagrams through a separate exercise. Students are given a manufacturing procedure from the
Handbook of Pharmaceutical Manufacturing Formulations on how to make coated ibuprofen tablets, read it, and then convert their readings into a flow diagram of this process, shown in Figure 2.

**Drug manufacturing**

An experiment developed on pharmaceutical processing equipment is the Fluidization of Pharmaceutical Ingredients Lab. This experiment is based on a polymer coating lab for freshmen developed by Rowan engineering faculty. The objective of the lab is to analyze the fluidization of a pharmaceutical ingredient, such as an excipient, and measure basic fluid/particle properties. To do this, students first determine three properties: bulk density, particle density, and bed porosity. This is done through a gravimetric analysis, where the students use a graduated cylinder and water to determine the bulk and particle densities, and then calculate the porosity of the substance using these two parameters. Students then compare the parameter values found experimentally to literature values using particulate databases. The second part of the experiment focuses on fluidization phenomena. The objective of this part is to determine fluidization regimes and the effect of process parameters related to fluidization. The setup of the fluidized bed is shown in Figure 3, in which the excipient is fluidized in air.

Students conduct an experiment to measure the bed height as a function of air flow rate. They notice through this exercise that as bed height starts to increase, fluidization has also started. Pressure drop readings across the column are also taken during this study. Through graphs of these variables, as seen in Figures 4, students observe where the slopes of the lines change, denoting transformation from packed bed to fluidized bed behavior. In addition, students receive an exercise in using online reference tools. This exercise asks the students to find an article, through library electronic search tools, that describes the use of fluidized beds in the pharmaceutical manufacture, and discuss it in the next class.

The pharmaceutical objective of this experiment is to show equipment used in transportation, granulation, coating, and drying of solids. Since the fluidized solid particles act like a fluid, they become much easier to transport through conventional conveying equipment. Students also see how excipient properties affect the fluidization process. The students gain this experience through an exercise that has them compare the Reynolds Number at minimum fluidization, $Re_{mf}$, of two different excipient substances; Avicel® (microcrystalline cellulose powder) and kaolin (white clay powder). The main difference between these two studies is the average particle size (1.4 µm for kaolin and 180 µm for Avicel®), which is the primary reason the Reynolds Number calculations at minimum fluidization are different. The Reynolds Number (Re) calculation gives students experience in units and conversions, requiring them to convert to one system of units and prove that it is dimensionless. Students are also introduced to fluid flow in calculations and conversion of volumetric flow rates.

**Figure 2.** The solution to the flow diagram exercise found in the Tablet Statistical Analysis Lab.

**Figure 3.** The fluidized bed apparatus used in the Fluidization of Pharmaceutical Ingredients Lab.
to a fluid velocity in the bed. Finally, they use a design equation to predict what the Reynolds Number at minimum fluidization (Remf) should be and compare that to their experimentally determined value. This equation, along with supplemental governing equations, is in Eqs. (6) through (9), and was adapted from Kunil and Levenspiel.\(^{13}\)

\[
\text{Re}_{mf} = \sqrt{\left(C_i^2 + C_2 \text{Ar}\right) - C_i} \tag{6}
\]

With:

\[
\text{Ar} = \frac{D_p^3 \rho_s (\rho_p - \rho_s) g}{\mu^2} \tag{7}
\]

\[
C_i = \frac{300 (1 - e_{mf})}{7} \tag{8}
\]

\[
C_2 = \frac{e_{mf}}{1.75} \tag{9}
\]

Where \(e_{mf}\) is the void fraction at minimum fluidization; \(D_p\) is the diameter of the particle; \(\rho_s\) is the density of the fluid; \(\rho_p\) is the particle density of the solid; and \(\mu\) is the viscosity of the fluid. In the Avicel® experiment, the design equation predicted a Reynolds number of 19.36, while experimental data determined a Reynolds number of 19.10, which is within 1.4% difference.

**Drug formulation/delivery**

One of the drug formulation experiments created focused on the design of a pharmaceutical delivery device. The Asthma Drug Delivery Lab compares three different drug delivery systems for asthma medicines. The first objective of the experiment is to have the students reverse engineer the three systems; a dry powder inhaler, a metered dose “rescue” inhaler, and a nasal spray. Secondly, the students determine the quality control measures of the inhalers and how they deliver a specific dosage each time used.

The dry powder inhaler, an ADVAIR Diskus®, is also known as a diskhaler. The students compare the production design of the Diskus® with a metered dose “rescue” inhaler and a nasal spray through a reverse engineering exercise. Only the ADVAIR Diskus® reverse engineering process is described in this paper, as it was the most technically complex device. First, the students brainstorm the drug delivery mechanism of the diskhaler, using the patient insert as the source of information. Most students will guess that there is some sort of puncture device that allows the medicine to enter the main chamber of the diskhaler, as it is described in the pamphlet as blisters being punctured open. Seeing the inner mechanisms gives the student insight into how the inhaler actually works, using a tearing mechanism to open the blister packets. Since the design utilizes blisters, the device ensures that only a certain amount of the active pharmaceutical substance is released for each use, keeping the rest of the powder fresh inside the individual blisters for subsequent doses. Figure 5 shows a student viewing the inside of the diskhaler, and a schematic is shown as a comparison. This schematic is based on a

**TABLE 3**

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Mass of Diskhaler Powder (g)</th>
<th>Mass of Metered Dose Inhaler (g)</th>
<th>Mass of Nasal Spray (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0130</td>
<td>0.0130</td>
<td>0.0867</td>
</tr>
<tr>
<td>2</td>
<td>0.0130</td>
<td>0.0128</td>
<td>0.0979</td>
</tr>
<tr>
<td>3</td>
<td>0.0127</td>
<td>0.0088</td>
<td>0.0989</td>
</tr>
<tr>
<td>4</td>
<td>0.0132</td>
<td>0.0107</td>
<td>0.0854</td>
</tr>
<tr>
<td>5</td>
<td>0.0126</td>
<td>0.0130</td>
<td>0.1004</td>
</tr>
<tr>
<td>6</td>
<td>0.0123</td>
<td>0.0014</td>
<td>0.0983</td>
</tr>
<tr>
<td>7</td>
<td>0.0130</td>
<td>0.0140</td>
<td>0.1022</td>
</tr>
<tr>
<td>8</td>
<td>0.0129</td>
<td>0.0148</td>
<td>0.1090</td>
</tr>
<tr>
<td>9</td>
<td>0.0124</td>
<td>0.0120</td>
<td>0.0991</td>
</tr>
<tr>
<td>10</td>
<td>0.0130</td>
<td>0.0121</td>
<td>0.0986</td>
</tr>
<tr>
<td>Average</td>
<td>0.0128</td>
<td>0.0125</td>
<td>0.0968</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>2.81·10⁻⁴</td>
<td>1.66·10⁻³</td>
<td>5.48·10⁻³</td>
</tr>
</tbody>
</table>
Figures 5. The inner mechanisms of an ADVAIR Diskus®. On the left is a sample of the student's reverse engineering findings, and on the right is a detailed schematic of a diskhaler from U.S. Patent Application 2009/0314291 A1.13 Parts a through d are the mouthpiece, opened blister pocket, opening station, and manifold cavity, respectively.

Students also have to discuss the ergonomics and aesthetics of each of the products, so that they also understand the importance of these two factors on product design in drug delivery.

The second half of this experiment has the students review the quality control aspect of the three devices by taking mass measurements of the doses being delivered and calculating the mean and standard deviation (Table 3). For more information on how these mass measurements were collected, refer to the Asthma Drug Delivery Lab posted on PharmaHUB. From this data, the students compare the standard deviations, and what that implies about the function of the devices. Students observe that the diskhaler has the lowest standard deviation of the three devices, which is due to the design of the device. Similar results are not obtained with the metered dose inhaler and the nasal spray because the metered dose inhaler involves a fluid that easily evaporates and the precision of the nasal spray depends on how well the apparatus is primed. These product designs enter into the discussion of why the standard deviations for those two designs have an order of magnitude difference from that of the diskhaler. Students are also tasked with looking up typical standard deviations for therapeutic dosage delivery.

Another experiment regarding drug formulation and delivery is the Dissolvable Strip Lab. In this experiment, students are tasked with investigating the dissolution rate of ingredients in dissolvable strips. Strip films have become an area of interest in the past few years as an alternative to conventional tablets and capsules, especially for patients suffering from dysphagia.13 Some examples of consumer products formulated into orally administered strips include breath fresheners, energy supplements, and analgesics for flu and sinus symptoms.13 In this lab, students work with Sheets™ brand energy strips, containing caffeine and blue food dye. Blue food dye in the product is used to model the release of a pharmaceutical ingredient. The students are to investigate the effect of temperature on the dissolution
rate by placing one strip in water kept at room temperature (~ 22 °C), and placing another in water at body temperature (~ 37 °C). To simulate the mouth, a shallow petri dish is filled with 25 mL of water, in which a strip is placed; absorbance measurements are taken at regular intervals, generating graphs as seen in Figure 6. The absorbance values are related to the concentration of the ingredients released by using a standardization curved developed at the beginning of the experiment.

The experiment introduces the students to spectrophotometry, and the principles related to the methodology used to measure solution concentration. This is done by having the students apply the Beer-Lambert law to determine the molar absorptivity coefficient of the blue food dye at both temperatures, as calculated in Eq. (10). For the Beer-Lambert Law, students use data from their experiment at a time of 80 minutes, which corresponds to when the absorbance readings should reach steady state.

$$\epsilon = \frac{A}{\ell c} = \frac{0.425}{(1 \text{ cm})(3.03 \cdot 10^{-3} \text{ M})} = 1.40 \cdot 10^{-4} \text{ M}^{-1} \text{ cm}^{-1}$$  \hspace{1cm} (10)

Where $A$ is the absorbance (dimensionless), $\ell$ is the measurement cell width, and $c$ is the molar concentration of the sample. The students should notice that the coefficients are identical between the two cases ($\epsilon_{22}$ and $\epsilon_{37}$ are $1.40 \cdot 10^{-4} \text{ M}^{-1} \text{ cm}^{-1}$), which determines that for the ranges used in this experiment, the temperature does not significantly affect the molar absorptivity coefficient. The students are then charged with determining how the Beer-Lambert law and molar absorptivity coefficients can be applied in other engineering applications. Some of the common answers will be wastewater treatment, product synthesis, and algae growth.

The pharmaceutical relevance of this experiment is that students are introduced to a novel drug delivery system. The students also see how the strip film quickly dissolves in water, indicating that the polymer used in the strips breaks down when it comes in contact with water. The concept of higher temperatures affecting the dissolution rate of the strip is also reinforced through an example involving rate laws. In this example, the students use absorbance readings and determine the rate law coefficient, $k$, for both experimental conditions. Upon calculating, the students see that the rate coefficient is higher for the body temperature experimental run than the room temperature study.

Some additional parts of this experiment have been developed based on advanced instrumentation and the available time. If a broader range spectrophotometer is available, absorbance data can be taken for caffeine at a wavelength of 273 nm. An agitated system can also be used to examine the convective effects on dissolution rate of the strip.

**Pharmacokinetics/pharmacodynamics**

An experiment developed on pharmacokinetics/pharmacodynamics uses Alka-Seltzer® to investigate the reaction mechanism behind an effervescent reaction. Students evaluate the reaction the tablet has when it comes in contact with water. This experiment, the Effervescence Reaction Lab, evaluates the effect of tablet manufacturing process on the rate of reaction. Students compare the effervescent reaction of a whole tablet of Alka-Seltzer® to the raw ingredients of an Alka-Seltzer® tablet that have been individually obtained. Both the tablet and raw ingredients are allowed to react with water separately, while students take residual mass measurements as time progresses. Students must determine why the whole tablet reacts faster. The students are provided information on

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**Figure 7.** Alka-Seltzer® Effervescence Reaction laboratory experiment comparing a whole tablet and the individual raw ingredients showing the deviation between actual and stoichiometric values of the effervescence reaction.
the production process which includes the milling step for the tablet’s ingredients, which is the process used to reduce the particle size. Therefore, with greater surface area and a more uniform composition, the reaction proceeds faster than the unmilled raw materials.

By having students measure the amount of mass that left the system, they determine the amount of carbon dioxide (CO$_2$) gas produced via the effervescence reaction. Using stoichiometry, the students also determine the amount of CO$_2$ they should have theoretically generated during the reaction. The stoichiometric equation is shown in Eq. (11).

$$C_6H_{12}O_6 (aq) + 3NaHCO_3 (aq) → 3H_2O(l) + 3CO_2 (g) + Na_2C_6H_2O_7 (aq)$$ (11)

Using these two values, the students determine the percent difference between their theoretical and experimentally observed values, as shown in Figure 7. They see that the longer the reaction continues the difference between theoretical values and experimental values starts to decrease. By having students determine the percent difference, they learn that theory does not always predict what actually happens in practice.

**CONCLUSIONS**

Our initial assessment efforts show that the experiments convey both desired pharmaceutical concepts and core engineering objectives. We have done preliminary assessment of the laboratory experiments and have underway assessment of our broader pharmaceutical engineering educational activities. We are presenting some of the results relevant to the experiments developed. Other results from our course development, problem sets, and laboratory activities are planned for a separate paper. Representative results using the Tablet Statistical Analysis Lab are provided, which involved three student groups. The students were individually given a pre-lab test to measure their knowledge of several pharmaceutical and statistical aspects that were covered in the laboratory experiment. Multiple-choice questions included several pharmaceutical concepts such as definition of an API and function of excipients, along with questions about appropriate use of F- and t-tests. A representative question about excipients would be “The substance used in a tablet to take up space in a pharmaceutical product is...” and a representative question about the F-test would be: “The purpose of an F-test is to...”. The correct answer to the excipient question and the F-test question is “filler” and “to compare two sets of data to one another,” respectively. After the experiment was completed, a post-lab test was performed and the average of the correct responses of the students is shown in Figure 8. This indicates that the students have a better understanding of pharmaceutical concepts and the purpose of statistical tests after conducting the experiment.

Students were given additional questions on the post-lab test to determine if the experiment helped to advance the broader educational objectives of increasing pharmaceutical interest and experimental methods. The survey asked the students to agree or disagree with a statement about their experience with the laboratory using a Likert scale (1 being a strong disagreement and 5 being a strong agreement with the statement). The statements used in the survey relate to the student’s interest in pharmaceutical engineering (I wish to pursue more studies in the field of pharmaceutical engineering), the pharmaceutical aspect of the laboratory (The experiment introduced...
Complete laboratory procedures, both student and instructor versions, are available through the pharmaceutical knowledge and training website, <www.PharmaHUB.org>.

a concept of pharmaceutical engineering), the utility of the statistical tests (I can apply the statistical principles I learned in this lab to other engineering problems), and the educational objectives of the experiment (I had to appropriately use laboratory equipment [scales, etc.] for data collection). The average responses showed that most students gave a response of 4 for all categories of statements (Figure 9). We have also solicited input from current employers about the industrial relevance of the experiments. Representative feedback from one of our pharmaceutical professionals indicates, “These experiments are valuable in exposing engineering students to principles of pharmaceutical engineering.”

The experiments developed can be easily integrated into Freshman-level engineering courses. These experiments illustrate basic engineering and science principles, while acquainting students with fundamentals of pharmaceutical engineering. The experiments convey concepts in pharmaceutical fundamentals, drug manufacture, drug formulation/delivery, and pharmacokinetics/pharmacodynamics. Experiments developed to date include: Tablet Statistical Analysis Lab; Asthma Drug Delivery Lab; Antacid Comparison Lab; Effervesence Reaction Lab; Fluidization of Pharmaceutical Substances Lab; Degradation of Dissolvable Strips Lab; Bandage Comparison Lab; and Creation of Dissolvable Strips Lab. The experiments can be used individually to meet specific educational objectives, such as applying statistical methods to manufacturing quality control, or grouped into a theme for more in-depth learning. The experiments have multiple parts that allow faculty to add more complexity or accomplish other learning objectives. These experiments can pique student interest in pharmaceutical engineering and provide background needed for advanced courses or laboratories. Complete laboratory procedures, both student and instructor versions, are available through the pharmaceutical knowledge and training website, <www.PharmaHUB.org>.

ACKNOWLEDGMENTS

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REFERENCES


This one-page column will present practical teaching tips in sufficient detail that ChE educators can adopt the tip. The focus should be on the teaching method, not content. With no tables or figures the column should be approximately 450 words. If graphics are included, the length needs to be reduced. Tips that are too long will be edited to fit on one page. Please submit a Word file to Phil Wankat <wankat@ecn.purdue.edu>, subject: CEE Teaching Tip.

APPROACH TEACHING USING RESEARCH SKILLS: A GUIDE FOR NEW FACULTY

DONALD P. VISO, JR.
The University of Akron

New faculty can take the mindset they already have developed for doing technical research and adapt it for teaching.

Scenario: You’ve trained for years in your technical area and are well prepared to do technical research. During your interview for a tenure-track faculty position, you have an interview with an associate dean—me. I’ve read your impressive 30-page research plan as well as your one-page teaching plan, half of which lists the courses you can teach. After I ask and you explain how you developed your research plan, I ask how you developed your teaching plan. Your answer is much shorter and indicates you are not well-informed. Then, I walk over to my bookshelf, bring back various journals and classic books in engineering education, and ask “why haven’t you included any references from these journals or from these books for your teaching plan in the way you have for your research plan? This is the literature for this field.” You stammer, thinking that this is a reasonable question and wonder why you have not even thought to do this. But then I explain that your response is the norm and this creates, hopefully, a teachable moment. You eagerly listen and write things down on a notepad.

Chances are you aren’t nearly as well prepared for an assistant professor’s teaching responsibilities as you are for research. Perhaps you were a teaching assistant and gave a lecture or two for your Ph.D. or postdoc advisors. But you do have something very useful on your side: you already have experience tackling new areas since you’ve been developing this skill as a graduate student and postdoc. Put this skill set to use for your teaching responsibilities by couching your approach to teaching as you would your technical research.

The following path is fairly typical for conducting technical research once you have an idea or area of interest.

1. Review the literature.
2. Join an organization and attend a conference to learn more about the state-of-the-art.
3. Discuss your research idea with colleagues.
4. Attend a workshop to refine your knowledge.
5. Do preliminary research for proof of concept.
6. Develop a research plan and submit a grant proposal.
7. Perform the research, evaluate your results, and fine-tune the methods.
8. Publish and present your results.

With the changes noted below, a similar path can be followed in doing scholarly teaching and classroom research.

1. Review the chemical engineering education literature (e.g., Chemical Engineering Education and ASEE Conference Proceedings) and pertinent textbooks.
2. Join an organization (e.g., AIChE and/or ASEE) and attend a conference.
3. Discuss teaching methods for this course with colleagues who have taught the course before.
4. Attend a workshop [e.g., the ASEE National Effective Teaching Institute (NETI)] to learn teaching methods that are more effective than lecture.
5. Teach the course the first time using teaching methods you are fairly familiar with, perhaps lecture interspersed with active learning methods.
6. Develop ideas to improve the course and discuss with a mentor or colleague.
7. Try your ideas in class, assess and evaluate your results, and modify as needed.

Although most engineering professors stop the process at this point, consider the next step.

8. Publish in the chemical engineering education literature and/or present your results at a conference.

Remember, you have well-honed skills in tackling new areas from your research. Put those to use to get off to a fast start in your teaching responsibilities as well.
Navigating the Grad School Application Process: A TRAINING SCHEDULE

GARRETT R. SWINDLEHURST AND LISA G. BULLARD

Through a simple step-by-step guide for navigating the graduate school application process, a graduate student who's been through the ringer and a faculty advisor who knows the ropes offer advice to walk prospective grad students through the process of successfully entering graduate school.

WARM UP

Summer: Start Stretching!

- Go to Google and search “National Science Foundation Graduate Research Fellowships” (NSF GRF). Call or e-mail the fellowship advising office on your campus and talk to them about this prestigious funding opportunity for grad school-bound researchers in science and engineering.
- Apply for the NSF GRF. The essays take a long time to perfect, so start working on them now.
- Google “Hertz Fellowship” and “National Defense Science and Engineering Graduate Fellowship” (NDSEG) and take a look at them as well. Applying for many different fellowships makes completing grad school applications easy, as you'll have much of the essay material already written. It also gives you a good chance to focus and really think about the application process and your future research.
- Register for a GRE testing session about one month from now. Just go ahead and set a date that currently works, and then work the rest of your schedule around preparing for it. Try to get one test in before October, so that you can retake it in October if you don’t do as well as you’d like. You can only register for one test session per month.
- If you pass on all other preparation for the GRE, complete the full practice test in the free POWERPREP II® software available from ETS (www.ets.org). Pretend that you are in a real test situation, complete with timing of sections and breaks. Doing practice tests in the computer environment is much more effective than doing pen-and-paper practice tests. The actual test is also long and quite fatiguing, so getting exposed to the physical stress of the real test environment is valuable.

Late October / Early November: Scouting

- Start visiting departmental websites and make a list of eight or so schools that you are considering by the beginning of October. Leave this list flexible until the end of November.
- Go to the AIChE National Student Conference. If you have completed undergraduate research, prepare a research poster and present it at the poster session (the application deadline is typically in early September). When not at your poster, go to the graduate recruitment fair and speak to professors from other departments. They are at the conference to find the best students for their graduate program, and if you're there, you can get “in” with the admissions or recruitment chair with a good one-on-one conversation. Receiving “offers” on the spot has been known to happen with a good first impression. Plus, your professors can introduce you to their colleagues who may serve on admissions committees—potentially garnering you another “in” with a program in which you're interested.
- NOTE: When applying to “graduate school,” you usually have to simultaneously apply to both the department of interest and the university’s Graduate School, the college that manages graduate education. This can be easy (there is a common online system for applying to many Graduate Schools) or difficult (vastly different essays required by the Graduate School and department). When selecting your programs of interest, take a quick survey to see into what category the application will fall — this can help you manage your time in the long run.
- Finish your NSF application before working on any grad school applications. More often than not, your statement of intent to the program of your choice will be adapted from some combination of your NSF essays.

Late November: Start Your Engines

- Be on the lookout for e-mails from programs offering to waive the application fee for their program. You may be able to apply to these departments with minimal extra effort, and in doing so, perhaps you'll discover something you didn’t see in them before.
- Choose four to eight schools to apply to and then talk to your academic mentor of choice about your selections. He or she can offer you feedback about the quality of the program and its faculty.
- Finalize the list of schools to which you’re going to apply.
• Bounce your thoughts and application choices off your professors who are alumni of those departments. They also will have good feedback about the strengths and weaknesses of where they did their Ph.D. work.

• Use an Excel spreadsheet to monitor your progress. Keep track of the application parts you have to submit, how/where/when to submit them, and money you have paid for applications. Ultimately, having this checklist of goals and progress will help you keep moving towards your personal submission deadline.

• Finish your Personal Statement and have as many people as possible give you feedback—professors and peers alike.

• Make a count of how many official transcripts you need. Order them all at once, early, and keep track of them. Make sure you order them before fall semester grades come in, unless you know you will be submitting applications after the New Year and that your fall grades will only raise your GPA.

WORKOUT 1:
Early / Mid-December: The Pre-Break Hustle

• Complete the applications "horizontally," not "vertically." Many of the applications are on similar hosting websites, or at least have the same components, and will let you save your progress. Doing each piece for all applications simultaneously is easier and will save time.

• Finish all digital components in "soft" format first, *i.e.*, not submitted yet. Then, in one big day, submit all the applications at one time, once you know that they are fully complete (this is where the Excel worksheet is useful). Not only does it feel great to get them all in together, but you will make sure that you don't lose track of anything.

• The same applies for items required in paper form, including official transcripts.

• Now you're over the major hurdle. Take the rest of the year off (aside from finishing fall classes!) and look forward to hearing back from some schools over break.

WORKOUT 2:
Late January / Early February: Let the Games Begin

• By now, you have some acceptances rolling in. Rejoice with each one, for it is a fantastic potential future for you! Beers or other celebratory measures are optional but recommended.

• Begin making a calendar of all the potential visit weekends for programs that accepted you. It's time to begin piecing together your schedule puzzle for Touring Season. Note any potential conflicts in scheduling among your top choices.

• For each of your top three to four programs, make it an utmost priority to respond that you will attend one of their scheduled visitation weekends. These organized weekends are much more fun and well-planned than private visits, and the professors have more time to meet with you.

• For programs high on your priorities list with only one visitation weekend, go ahead and book it. You have to make the best decision with the information that you have available at the time.

• Hopefully, you will hear back from all of your programs by the end of February. By then, you might also have taken a visitation weekend already, which brings us to our next point...

Late February / Early March: The Good Times Roll

• Visitation weekends are awesome—go on them all, if you can. You are treated like a rock star, get to see the department, and travel on a student budget (aka, free!). What's not to like? Granted...

• ...some people get weary of traveling. If you do, visit only the schools you are really serious about. This is something you just have to gauge for yourself—there are only so many weekends from mid-February to mid-April. Four visits are about average, while some people can manage doing seven. Establish a touring schedule that works for you.

• Make lots of friends on these visits. Meet everyone, and ask them about their visits and impressions. Talking about it will help you make a decision in the end, and maybe get you a future roommate.

• Finish all coursework before you leave for a trip. You won’t have time or energy to work on anything on the trip, despite your best intentions.

• Take lots of notes. It’s tedious at the time, and you won’t think there’s any way you could forget that professor or project, but you will. Spending the flight back from each weekend noting down your impressions is a good idea. Those notes are tools to prompt phone calls to professors or students later, and they will ultimately help you make a decision.

TAPERING:
Early April: Decision Time

• Choosing a graduate program is the chemical engineering career equivalent of accepting a marriage proposal. Analogously, it may be the most important decision you have ever had to make. There are many factors to weigh, but in the end, it's your decision alone. Here are a few tips:

• Talk to someone about it. In fact, talk to everyone about it. If you have a sympathetic friend, complaining about how hard the decision is may even help ease the stress. Either way, just actively thinking about the decision in this way will help you approach your best-reasoned choice—or otherwise, the gut feeling that you’ve always been moving towards anyway.

• Make your decision in early April if possible. Your first choice school will be grateful, and your other candidate schools will appreciate knowing of your decision not to attend so they can roll your offer over to another applicant prior to April 15.

• Once you’ve made a decision, don’t second guess yourself. Finish strong, enjoy your graduation festivities, and look forward to the grad school race ahead. But remember, it's a marathon, not a sprint!
PRESENTING:

CEE's Annual
Grad Guide
for 2014-2015

The following pages feature schools that offer graduate education programs in chemical engineering and related fields. By advertising their programs in this annual graduate education issue, and on our website at <http://www.che.ufl.edu/cee/>, these schools have financially supported CEE's ability to continue serving the needs of the international community of educators in chemical engineering.

CEE (Chemical Engineering Education) is the premier archival journal for chemical engineering educators.
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Graduate Education in Chemical and Biomolecular Engineering

Teaching and research assistantships as well as industrially sponsored fellowships available. In addition to stipends, tuition and most fees are waived. PhD students may get some incentive scholarships.

- Castaneda: Electrochemistry & Corrosion, Coatings Damage/Performance, Special Alloys
- Chase: Multiphase Processes, Nanofibers, Filtration, Coalescence
- Cheng: Biomaterials, Protein Engineering, Drug Delivery and Nanomedicine
- Cheung: Polymerization in Nanostructured Fluids, Supercritical Fluid Processing
- Cong: Localized Corrosion, Environmentally Assisted Cracking, Corrosion Inhibition
- Elliott: Molecular Simulation, Phase Behavior, Physical Properties, Supercritical Fluids
- Evans: Material Processing and CVD Modeling, Plasma Enhanced Deposition and Crystal Growth Modeling
- Ju: Renewable Bioenergy, Environmental Bioengineering
- Leipzig: Cell and Tissue Mechanobiology, Biomaterials, Tissue Engineering
- Lillard: Corrosion, Oxide Films, SCC and Hydrogen Interactions and Metals
- Liu: Biointerfaces, Biomaterials, Biosensors, Tissue Engineering
- Monty: Reaction Engineering, Biomimicry, Microsensors
- Newby: Surface Modification, Biomaterials, Antifouling/Biofilm/Biocorrosion
- Payer: Corrosion & Electrochemistry, Systems Health Monitoring and Reliability, Materials Performance and Failure Analysis
- Peng: Materials, Catalysis and Reaction Engineering
- Puskas: Biomaterials, Green Polymer Chemistry and Engineering, Biomimetic Processes
- Visco: Thermodynamics, Computer-aided Molecular Design
- Zheng: Computational Biophysics, Biomolecular Interfaces, Biomaterials
- Zhu: Advanced Energy and Nanomaterials

Environmental Remediation
The Chemical and Materials Engineering Department at the University of Alabama Huntsville offers graduate programs leading to an M.S. or a Ph.D. in advanced areas of chemical engineering, materials science and engineering and biotechnology. Our faculty are dedicated to advancing our understanding of problems in mass transfer, fluid mechanics, materials processing, thin films and adhesion, energy conversion and storage, structure of nano-materials, gene expression, bioinformatics and medical diagnostics. Our faculty work closely with several scientists at the HudsonAlpha Institute for Biotechnology located in Huntsville, Alabama offering students an outstanding opportunity to work on understanding the relationship between genes, gene sequences and the disease process. Our faculty are also dedicated to creating and implementing innovative ideas in teaching which include the use of multimedia technologies and open source software for computing and simulation.
STUDY CHEMICAL AND MATERIALS ENGINEERING
AT THE UNIVERSITY OF ALBERTA, CANADA

The Department of Chemical and Materials Engineering at the University of Alberta is part of the Faculty of Engineering, which ranks in size among the top five percent of over 400 engineering schools in North America, with about 4,000 undergraduate and 1,600 graduate students.

We offer outstanding research facilities including the: National Institute for Nanotechnology; Canadian Centre for Clean Coal/Carbon and Mineral Processing Technologies; Canadian Centre for Welding and Joining; and Institute for Oil Sands Innovation. We also offer the only program in Canada dedicated to Engineering Safety and Risk Management.

Our programs are taught by award-winning professors including a Canadian Excellence Research Chair, seven Canadian Research Chairs, seven Natural Sciences and Engineering Research Council Industrial Research Chairs, making up a faculty of approximately 60 members.

With MSc and PhD programs in chemical engineering and materials engineering and specializations in: advanced materials, process control and systems engineering, nano and regenerative medicine, surface and interfacial science, and energy and natural resources.

All full-time graduate students in research programs receive a stipend. Annual research funding for our Department is over $14 million. Externally sponsored funding to support research in the Faculty of Engineering has increased to over $50 million each year—the largest amount of any Faculty of Engineering in Canada.

Department of Chemical and Materials Engineering,
University of Alberta
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Phone: (780) 492-3321 | Fax: (780) 492-2881
Email: cmeinfo@ualberta.ca

For more information visit:
www.cme.engineering.ualberta.ca

UNIVERSITY OF ALBERTA
DEPARTMENT OF CHEMICAL & MATERIALS ENGINEERING

“uplifting the whole people”
— HENRY MARSHALL TURET, FOUNDING PRESIDENT, 1908
FACULTY / RESEARCH INTERESTS

ROBERT G. ARNOLD, Professor (CalTech)
- Microbiological Hazardous Waste Treatment, Metals Speciation and Toxicity

JAMES C. BAYGENTS, Associate Professor and
- Associate Dean of Engineering (Princeton)
- Fluid Mechanics, Transport and Colloidal Phenomena, Bioseparations

PAUL BLOWERS, Distinguished Professor
- (Illinois, Urbana-Champaign)
- Chemical Kinetics, Catalysis, Environmental Foresight, Green Design

WENDELL ELA, Professor (Stanford)
- Particle-Particle Interactions, Environmental Chemistry

JAMES FARRELL, Professor (Stanford)
- Sorption/desorption of Organics in Soils

JAMES A. FIELD, Professor and Chair (Wageningen University)
- Bioremediation, Environmental Microbiology, Hazardous Waste Treatment

DOMINIC GERVASIO, Research Professor (Case Western Reserve)
- Electrocatalysis, Ion Conductors, Electrochemistry including: Electrop­lating, Corrosion and Energy Storage and Power Sources including Fuel Cells, Batteries, Fuels, Fuel Reforming and Solar Cells

ROBERTO GUZMAN, Professor (North Carolina State)
- Affinity Protein Separations, Polymeric Surface Science

ANTHONY MUSCAT, Professor (Stanford)
- Kinetics, Surface Chemistry, Surface Engineering, Semiconductor Processing, Microcontamination

KIMBERLY OGDEN, Professor (Colorado)
- Bioreactors, Bioremediation, Organics Removal from Soils

ARA PHILIPOSSIAN, Professor (Tufts)
- Chemical/Mechanical Polishing, Semiconductor Processing

EDUARDO SÁEZ, Distinguished Professor (UC, Davis)
- Polymer Flows, Multiphase Reactors, Colloids

GLENN L. SCHRADER, Professor (Wisconsin)
- Catalysis, Environmental Sustainability, Thin Films, Kinetics, Solar Energy

FARHANG SHADMAN, Regents’ Professor (Berkeley)
- Reaction Engineering, Kinetics, Catalysis, Reactive Membranes, Microcontamination, Semiconductor Manufacturing

REYES SIERRA, Professor (Wageningen University)
- Environmental Biotechnology, Semiconductor Manufacturing, Wastewater Treatment

SHANE A. SNYDER, Professor (Michigan State University)
- Endocrine Disruptor and Emerging Contaminant Detection and Treatment, Water Reuse Technologies and Applications

ARMIN SOROOSHIAN, Assistant Professor (CalTech)
- Aerosol Composition and Hygroscopicity, Climate Change

For further information
http://www.che.arizona.edu
Graduate Coordinator
Department of Chemical and Environmental Engineering
PO. BOX 210011
The University of Arizona
Tucson, AZ 85721

The University of Arizona is an equal opportunity educational institution/equal opportunity employer.
Women and minorities are encouraged to apply.

Chemical and Environmental Engineering

at

THE UNIVERSITY OF

ARIZONA

TUCSON ARIZONA

The Department of Chemical and Environmental Engineering at the University of Arizona offers a wide range of research opportunities in all major areas of chemical engineering and environmental engineering. Our department offers a comprehensive approach to sustainability which is grounded on the principles of conservation and responsible management of water, energy, and material resources. Research initiatives in solar and other renewable energy, desalination, climate modeling, and sustainable nanotechnology are providing innovative solutions to the challenges of environmental sustainability. A significant portion of research effort is devoted to areas at the boundary between chemical and environmental engineering, including environmentally benign semiconductor manufacturing, environmental remediation, environmental biotechnology, and novel water treatment technologies. The department offers a fully accredited undergraduate degree in chemical engineering, as well as MS and PhD degrees in both chemical and environmental engineering. Financial support is available through fellowships, government and industrial grants and contracts, teaching and research assistantships.

Tucson is a growing modern city that retains much of the old Southwestern atmosphere.
The Ralph E. Martin Department of Chemical Engineering at the University of Arkansas offers graduate programs leading to M.S.ChE and Ph.D. degrees. Qualified applicants are eligible for financial aid. Annual departmental Ph.D. stipends provide $20,000, Doctoral Academy Fellowships provide up to $30,000, and Distinguished Doctoral Fellowships provide $40,000.

For stipend and fellowship recipients, all tuition is waived. Applications received before April 1 will be given first consideration. Fellowship applications must be received by January 15.

Areas of Research

- Biochemical and Bioprocess Engineering
- Biomedical Engineering
- Chemical Hazards Assessment
- Energy & Environmental Engineering
- Engineering Education
- Materials
- Membranes & Advanced Separations
- Nanotechnology
- Process Design & Systems Engineering
- Sustainability

Faculty

M.D. Ackerson
R.E. Babcock
R.R. Beitle
E.C. Clausen
J.A. Havens
J. Herman
C.N. Hestekin
J.A. Hestekin
W.A. Myers

W.R. Penney
D.K. Roper
S.L. Servoss
T.O. Spicer
G.J. Thoma
R.K. Ulrich
H.L. Walker
S.R. Wickramasinghe

For more information, contact Dr. Jerry Havens • jhavens@uark.edu • 479-575-4951
Chemical Engineering Graduate Program Information • www.cheg.uark.edu/graduate.php
CHEMICAL ENGINEERING
AT AUBURN UNIVERSITY

ALTERNATIVE ENERGY & FUELS BIOCHEMICAL ENGINEERING BIOMATERIALS BIOMEDICAL ENGINEERING BIOPROCESSING & BIOENERGY CATALYSIS & REACTION ENGINEERING COMPUTER-AIDED ENGINEERING DRUG DELIVERY ENERGY CONVERSION & STORAGE ENVIRONMENTAL BIOTECHNOLOGY FUEL CELLS GREEN CHEMISTRY MATERIALS MEMS & NEMS MICROFIBROUS MATERIALS NANOTECHNOLOGY POLYMERS PROCESS CONTROL PULP & PAPER SUPERCritical FLUIDS SURFACE & INTERFACIAL SCIENCE SUSTAINABLE ENGINEERING MOLECULAR THERMODYNAMICS

W. ROBERT ASHURST University of California, Berkeley
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ROBERT P. CHAMBERS University of California, Berkeley
VIRGINIA A. DAVIS Rice University
ALLAN E. DAVID University of Maryland
STEVE R. DUKE University of Illinois at Urbana-Champaign
MARIO R. EDEN Technical University of Denmark
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THOMAS R. HANLEY Virginia Tech Institute
YOO N Y. LEE Iowa State University
ELIZABETH A. LIPKE Rice University
GLENNON MAPLES Oklahoma State University
RONALD D. NEUMANN The Institute of Paper Chemistry
JAMES RADICH University of Notre Dame
CHRISTOPHER B. ROBERTS University of Notre Dame
BRUCE J. TATARCHUK University of Wisconsin
JIN WANG University of Texas at Austin

AUBURN UNIVERSITY offers a challenging graduate curriculum and research program that prepares its PhD and MS graduates for successful careers. Thanks to an exceptional team of educators and researchers, our department remains at the forefront of discovery and innovation. The size and strength of Auburn's research program provides important advantages for graduate students. Auburn maintains a top ranking in research awards per faculty member, allowing the department to provide excellent fellowships and assistantships and offer cutting-edge research equipment in our laboratories.

During the past decade, Auburn chemical engineering has continued to increase in size and strength, allowing the program to provide distinct opportunities and advantages to its students, and produce innovative research.

FOR MORE INFORMATION
Director of Graduate Recruiting
Department of Chemical Engineering
Auburn, AL 36849-5127
Phone 334.844.4827
Fax 334.844.2063
www.eng.auburn.edu/chen
chemical@eng.auburn.edu
Financial assistance is available to qualified applicants.

Auburn University is an equal opportunity educational institution/employer.
Vancouver is the largest city in Western Canada, ranked the 3rd most livable place in the world. Vancouver's natural surroundings offer limitless opportunities for outdoor pursuits throughout the year - hiking, canoeing, mountain biking, skiing... In 2010, the city hosted the Olympic and Paralympic Winter Games.

The University of British Columbia is the largest public university in Western Canada and is ranked among the top 40 institutes in the world by Newsweek magazine, the Times Higher Education Supplement and Shanghai Jiao Tong University.

Faculty of Applied Science

CHEMICAL AND BIOLOGICAL ENGINEERING

www.chbe.ubc.ca

MASTER OF APPLIED SCIENCE (M.A.SC.)
MASTER OF ENGINEERING (M.ENG.)
MASTER OF SCIENCE (M.SC.)
DOCTOR OF PHILOSOPHY (PH.D.)

Currently about 170 students are enrolled in graduate studies. The program dates back to the 1920s. The department has a strong emphasis on interdisciplinary and joint programs, in particular with the Michael Smith Laboratories (MSL), Pulp and Paper Centre (PPC), Clean Energy Research Centre (CERC) and the BRIDGE program which links public health, engineering and policy research.

Main Areas of Research

Biological Engineering
Biochemical Engineering • Biomedical Engineering • Protein Engineering • Blood research • Stem Cells

Energy
Biomass and Biofuels • Bio-oil and Bio-diesel • Combustion, Gasification and Pyrolysis • Electrochemical Engineering • Fuel Cells • Hydrogen Production • Natural Gas Hydrates

Process Control
Pulp and Paper

Reaction Engineering

Environmental and Green Engineering
Emissions Control • Green Process Engineering • Life Cycle Analysis • Water and Wastewater Treatment • Waste Management • Aquacultural Engineering

Particle Technology
Fluidization • Multiphase Flow • Fluid-Particle Systems • Particle Processing • Electrostatics

Kinetics and Catalysis
Polymer Rheology

Financial Aid
Students admitted to the graduate programs leading to the M.A.Sc, M.Sc or Ph.D. degrees receive at least a minimum level of financial support regardless of citizenship (approx. $19,000/year for M.A.Sc and M.Sc and $21,000/year for Ph.D). Teaching assistantships are available (up to approx. $1,000 per year). All incoming students will be considered for several Graduate Students Initiative (GSI) Scholarships of $5,000/year and 4-year Doctoral Fellowships Scholarships of approx. $18,000/year.

Mailing address: 2360 East Mall, Vancouver B.C., Canada V6T 1Z3 • gradsec@chbe.ubc.ca • tel: +1 (604) 822-3457

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The Department of Chemical and Petroleum Engineering at the University of Calgary, Schulich School of Engineering delivers one of the highest calibre graduate engineering programs in the world with specializations in Chemical Engineering, Petroleum Engineering, Energy & Environmental Engineering, and Biomedical Engineering.

- Internationally recognized graduate program leading ground-breaking research with excellent facilities and generous financial support.
- Unique internationally for its high concentration of researchers working in energy relevant disciplines.
- Opportunity to interact with Canadian oil and gas industry on solving real-world problems.
- Ranked as the fifth most livable city in the world.*
- An hour's drive away from the spectacular Rocky Mountains with easy access to Banff.

* Economist Intelligence Unit 2012 rankings

**AREAS OF RESEARCH INCLUDE:**

- **Chemical:** Catalysis; modeling, simulation & optimization; process control & dynamics; reaction engineering & chemical kinetics; rheology (polymers, suspensions & emulsions); separation operations; thermodynamics & phase equilibria; transport phenomena (deposition in pipelines, diffusion, dispersion, flow in porous media, heat transfer); nanotechnology; nanoparticle research; polymer nanocomposites
- **Petroleum:** Drilling engineering; improved gas recovery (coal bed methane, gas hydrates, tight gas); improved oil recovery (SAGD, VAPEx, EOR, in-situ combustion); production engineering; reservoir characterization; reservoir engineering & modeling; reservoir geomechanics & simulation
- **Environmental:** Air pollution control; alternate energy sources; greenhouse gas control & CO2 sequestration; life cycle assessment; petroleum waste management & site remediation; solid waste management; water & wastewater treatment
- **Biomedical:** Cell & tissue engineering; mechano biology; biopolymers; protein production; blood filtration; microvascular systems; stem cell bioprocess engineering (media & reagent development, bioreactor protocols); medical diagnostics; regenerative medicine.

**FACULTY**

- U. Sundararaj, Head (Minnesota)
- I. Abedi (Toronto)
- R. Aguilera (Colorado School)
- S. M. Farouq Ali (Penn State)
- J. Azaiez (Stanford)
- L. A. Behie (Western Ontario)
- I. Bergerson (Carnegie-Mellon)
- S. Chen (Regina)
- Z. Chen (Purdue)
- M. Clarke (Calgary)
- A. De Vischer (Ghent, Belgium)
- M. Dong (Waterloo)
- M. W. Foley (Queen's)
- I. D. Gates (Minnesota)
- H. Hassanzadeh (Calgary)
- H. Hejazi (Calgary)
- J. M. Hill (Wisconsin)
- M. Hussein (McGill)
- A. A. Jeje (MIT)
- J. Jensen (Texas, Austin)
- M. S. Kallos (Calgary)
- A. Kantzas (Waterloo)
- K. Karan (Calgary)
- N. Mahinpey (Toronto)
- B. B. Mani (Univ. Washington)
- A. K. Mehrotra (Calgary)
- S. A. Mehta (Calgary)
- R. G. Moore (Alberta)
- N. Nassar (Calgary)
- P. Pereira Almada (France)
- K. Rinker (North Carolina)
- E. Roberts (Cambridge)
- H. Sarma (Alberta)
- H. De la Hoz Seigler (Alberta)
- H. Sen (Calgary)
- H. Song (Ohio State Univ.)
- M. Trifkovic (Western Ontario)
- H. W. Yarranton (Alberta)

**FOR ADDITIONAL INFORMATION, CONTACT:**

Associate Head, Graduate Studies
Department of Chemical and Petroleum Engineering, University of Calgary
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cpe-grad@ucalgary.ca

schulich.ucalgary.ca/graduateeducation
The Chemical & Biomolecular Engineering Department at the University of California, Berkeley, one of the preeminent departments in the field, offers graduate programs leading to the Doctor of Philosophy or a Master of Science in Product Development.

For more information visit our website at:

http://cheme.berkeley.edu
FOCUS AREAS

- Biomolecular and Cellular Engineering
- Process Systems Engineering
- Materials Manufacturing

GENERAL THEMES

- Energy and Chemicals
- The Environment
- Health Care

PROGRAMS

UCLA's Chemical and Biomolecular Engineering Department offers a program of education and research linking fundamental engineering science and industrial practice. Our Department has strong graduate research programs in Biomolecular Engineering, Energy and Environment, Engineering of Materials, and Process Systems Engineering.

Fellowships are available for outstanding applicants interested in Ph.D. degree programs. A fellowship includes a waiver of tuition and fees plus a stipend.

Located five miles from the Pacific Coast, UCLA's attractive 417-acre campus extends from Bel Air to Westwood Village. Students have access to the highly regarded engineering and science programs and to a variety of experiences in theatre, music, art, and sports on campus.

CONTACT

Admissions Office
Chemical and Biomolecular Engineering Department
5531 Boelter Hall • UCLA • Los Angeles, CA 90095-1592
Telephone at (310) 825-9063 or visit us at www.chemeng.ucla.edu
RESEARCH FOR A GREENER WORLD

The Department of Chemical and Environmental Engineering at the University of California Riverside is at the forefront of our nation’s commitment to energy independence and sustainability. Our four fields of application — clean air, fresh water, human health and sustainable energy — are supported by six core areas of research strength:


WE ENGINEER EXCELLENCE

The Graduate Program offers the M.S. and Ph.D. degrees in Chemical and Environmental Engineering. Graduates of the program in Chemical and Environmental Engineering are ready for careers in the fastest growing sectors of engineering with salaries among the highest of all college graduates. And they are fully prepared to contribute to the nation’s priority challenges in energy, security, clean air and water, or anything else.

NRC RANKINGS

The National Research Council’s (NRC) data-based assessment of U.S. Research doctorate programs demonstrated the excellence of the Department of Chemical and Environmental Engineering’s faculty and the rapid rise in the quality of its graduate program. CEE was ranked in the NRC’s top quartile.

UC RIVERSIDE

The University of California, Riverside (UCR) is the fastest growing and most ethnically diverse of the 10 campuses of the University of California. UCR is located on over 1,100 acres at the foot of the Box Springs Mountains, about 50 miles east of Los Angeles. Our picturesque campus is virtually equidistant from the desert, the mountains, and the ocean. UCR provides an ideal setting for students, faculty, and staff seeking to study, work, and live in a community steeped in rich heritage that offers a dynamic mix of arts and entertainment and an opportunity for affordable living.

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UC SANTA BARBARA
Chemical Engineering

Award-Winning Faculty
Bradley F. Chmelka
Patrick S. Daugherty
Michael F. Doherty
Francis J. Doyle III
Glenn H. Fredrickson, NAE
Michael J. Gordon
Song-I Han
Matthew E. Helgeson
Jacob Israelachvili, NAE, NAS, FRS
Edward J. Kramer, NAE
L. Gary Leal, NAE
Eric McFarland
Samir Mitragotri
Michelle A. O'Malley
Baron G. Peters
Susannah L. Scott
Rachel Segalman
M. Scott Shell
H. Tom Soh
Todd M. Squires

Research Strengths
Biomaterials and bioengineering
Energy, catalysis, and reaction eng.
Complex fluids and polymers
Electronic and optical materials
Fluids and transport phenomena
Molecular thermodynamics and simulation
Process systems engineering
Surfaces and interfacial phenomena

Interdisciplinary Centers and Programs
California Nanosystems Institute
Center for Bioengineering
Center for Control, Dynamical Systems, and Computation
Center for Polymers and Organic Solids
Complex Fluids Design Consortium
Dow Materials Institute
Institute for Collaborative Biotechnologies
Institute for Energy Efficiency
International Center for Materials Research
Kavli Institute for Theoretical Physics
Materials Research Laboratory
Mitsubishi Chemicals Center for Advanced Materials

Interdisciplinary research and entrepreneurship are hallmarks of Engineering at UC Santa Barbara. Many graduate students choose to be co-advised.

Located on the Pacific Coast about 100 miles northwest of Los Angeles, the UCSB campus has more than 20,000 students.

Doctoral students in good academic standing receive financial support via teaching and research assistantships. For additional information and to complete an application, visit www.chemengr.ucsb.edu or contact chegrads@engineering.ucsb.edu.
Arrr! Are ye up for an adventure?

Amast! If it's excitement and reward ye be after, set sail for graduate study in the Department of Chemical Engineering at Carnegie Mellon. Ay, fill yer mental coffers to the brim with a booty of knowledge and research skills from the frontiers of chemical engineering. Apply smartly and join the sweet trade. Savvy?
The chemical engineering department at the Case School of Engineering, one of the oldest in the country, offers cutting-edge research programs with field-leading faculty and world-class partner institutions. Our labs are tackling today's toughest engineering challenges in: energy, materials and biological applications.

**Energy and Electrochemical Systems**
- Fuel Cells and Batteries
- Electrochemical Engineering
- Energy Storage
- Electrodeposition

**Advanced Materials and Devices**
- Synthetic Diamond
- Coatings, Thin Films and Surfaces
- Microsensors
- Polymer Nanocomposites
- Nanomaterials and Nanosynthesis
- Particle Science and Processing
- Molecular Simulations
- Microplasmas and Microreactors

**Biological Applications**
- Cell and Tissue Engineering
- Transport in Biological Systems
- Biomedical Sensors and Actuators
- Neural Prosthetic Devices

**Faculty in the Department of Chemical and Biomolecular Engineering**
- Rohan N. Akolkar, PhD
  Case Western Reserve
- John C. Angus, PhD
  University of Michigan
- Hariraha Baskaran, PhD
  Pennsylvania State University
- Donald L. Feke, PhD
  Princeton University
- Daniel J. Lacks, PhD
  Harvard University
- Uziel Landau, PhD
  UC Berkeley
- Chung-Chiun Liu, PhD
  Case Institute of Technology
- J. Adin Mann Jr., PhD
  Iowa State University
- Heidi B. Martin, PhD
  Case Western Reserve
- Syed Qutubuddin, PhD
  Carnegie Mellon University
- R. Mohan Sankaran, PhD
  California Institute of Technology
- Robert F. Savinell, PhD
  University of Pittsburgh
- Jesse S. Wainright, PhD
  Case Western Reserve

For more information about research opportunities, admission and financial support, email chemeng@case.edu or visit engineering.case.edu/eche
Opportunities for Graduate Study in Chemical Engineering at the

UNIVERSITY OF CINCINNATI

M.S. and Ph.D. Degrees in Chemical Engineering

Faculty

A.P. Angelopoulos
Gregory Beaucage
Steven Clarson
Carlos Co
Junhang Dong
Rakesh Govind
Vadim Guliants
Chia-chi Ho
Jude Iroh
Yuen-Koh Kao
Soon-Jai Khang
Vikram Kuppa
Joo-Youp Lee
Dale Schaefer
Vesselin Shanov
Peter Smirniotis
Stephen W. Thiel

Financial Aid Available

The University of Cincinnati is committed to a policy of non-discrimination in awarding financial aid.

For Admission Information Contact
Barbara Carter
Graduate Studies Office
College of Engineering and Applied Science
Cincinnati, OH 45221-0077
313-556-5157
Barbara.carter@uc.edu
or
Professor Peter Smirniotis
The Chemical Engineering Program
Department of Biomedical, Chemical & Environmental Engineering
Cincinnati, Ohio 45221
panagiotis.smirniotis@uc.edu

Emerging Energy Systems
Catalytic conversion of fossil and renewable resources into alternative fuels, such as hydrogen, alcohols and liquid alkanes; solar energy conversion; inorganic membranes for hydrogen separation; fuel cells, hydrogen storage nanomaterials

Environmental Research
Mercury and carbon dioxide capture from power plant waste streams, air separation for oxycombustion; wastewater treatment, removal of volatile organic vapors

Molecular Engineering
Application of quantum chemistry and molecular simulation tools to problems in heterogeneous catalysis, (bio)molecular separations and transport of biological and drug molecules

Catalysis and Chemical Reaction Engineering
Selective catalytic oxidation, environmental catalysis, zeolite catalysis, novel chemical reactors, modeling and design of chemical reactors, polymerization processes in interfaces, membrane reactors

Membrane and Separation Technologies
Membrane synthesis and characterization, membrane gas separation, membrane filtration processes, pervaporation; biomedical, food and environmental applications of membranes; high-temperature membrane technology, natural gas processing by membranes; adsorption, chromatography, separation system synthesis, chemical reaction-based separation processes

Biotechnology
Nano/microbiotechnology, novel bioseparation techniques, affinity separation, biodegradation of toxic wastes, controlled drug delivery, two-phase flow

Polymers
Thermodynamics, polymer blends and composites, high-temperature polymers, hydrogels, polymer rheology, computational polymer science, molecular engineering and synthesis of surfactants, surfactants and interfacial phenomena

Bio-Applications of Membrane Science and Technology
This IGERT program provides a unique educational opportunity for U.S. Ph.D. students in areas of engineering, science, medicine, or pharmacy with above focus. This program is supported by a five-year renewable grant from the National Science Foundation. The IGERT fellowship consists of an annual stipend of $30,000 for up to three years.

Institute for Nanoscale Science and Technology (INST)
INST brings together three centers of excellence—the Center for Nanoscale Materials Science, the Center for BioMEMS and Nanobiosystems, and the Center for Nanophotonics—composed of faculty from the Colleges of Engineering, Arts and Sciences, and Medicine. The goals of the institute are to develop a world-class infrastructure of enabling technologies, to support advanced collaborative research on nanoscale phenomena.
RESEARCH AREAS

Biomaterials and Biotransport
- atherogenesis, bio-fluid flow, self-assembled biomaterials

Catalysis
- Catalyst design, reaction kinetics, electrocatalysis

Colloid Science and Engineering
- directed assembly, novel particle technology

Complex Fluids and Multiphase Flow
- boiling heat transfer, emulsions, rheology, suspensions

Energy Generation and Storage
- batteries, gas hydrates, thermal energy storage

Interfacial Phenomena and Soft Matter
- device design, dynamic interfacial processes

Nanomaterials and Self Assembly
- catalysts, patchy particles, sensors

Polymer Science and Engineering
- polymer processing, rheology

Powder Science and Technology
- pharmaceutical formulations, powder flow

INSTITUTES

Levich Institute for Physicochemical Hydrodynamics
- directed by Morton M. Denn
- Albert Einstein Professor of Science and Engineering

Energy Institute
- directed by Sanjoy Banerjee
- Distinguished Professor of Chemical Engineering

www.che engr.ccny.cuny.edu  
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212 650 6671
CLEMSON

CHEMICAL AND BIOMOLECULAR ENGINEERING

Clemson University is on the shores of Lake Hartwell at the foothills of the Blue Ridge Mountains in South Carolina. The world class research, great weather, and recreational activities make Clemson an ideal place to live and learn.

The faculty of the Department of Chemical and Biomolecular Engineering is a diverse team of dedicated research and teaching professionals. Our knowledge and research efforts have generated numerous publications and national awards. Because of this, we have created and are involved with several multi-million dollar projects with the U.S. Department of Energy, National Science Foundation, National Institutes of Health, Army and Air Force Research Labs, along with other institutions and corporations.

In addition to individual research groups, the department is home to two research centers: The Center for Advanced Engineering Fibers and Films (CAEFF) and The Center for Bioelectronics, Biosensors, and Biochips (C3B).

Our research programs focus on energy, biotechnology, advanced materials, and modeling and simulation.

FACULTY

Mark A. Blenner (Columbia U.) Asst. Professor; Protein and Metabolic Engineering, Synthetic Biology, Biocatalysis, Biosensors, Biorefining

David A. Bruce (Georgia Tech.) Professor; Catalysis, Kinetics, Renewable Chemicals, Molecular Modeling

Rachel B. Getman (Notre Dame) Asst. Professor; Computational Catalysis involving Complex Systems, Catalysis in Metal-Organic Frameworks, Rational Catalyst Design

Anthony Guiseppi-Elie (MIT) Professor & C3B Director; Bioelectronics, Biosensors, Biochips

Douglas E. Hirt (Princeton) Professor & Chair; Polymer Films, Biopolymers, Surface Modification

Scott M. Husson (UC Berkeley) Professor; Bioseparations, Advanced Separation Materials, Sustainable Water and Energy Production

Christopher L. Kitchens (Auburn) Assoc. Professor; Green Chemistry and Engineering, Nanomaterial Design for Biomedical and Environmental Applications, Nanocomposites for Renewable Resources

Amod A. Ogale (U. Delaware) Dow Chemical Professor & CAEFF Director; Carbon and Polymer Fibers, Films, Composites

Mark E. Roberts (Stanford) Asst. Professor; Conducting Polymers, Responsive Electrolytes, Electrochemical Systems

Sapna Sarupria (RP1) Asst. Professor; Molecular Modeling, Statistical Mechanics, Biological Self-Assembly


Mark C. Thies (U. Delaware) Dow Chemical Professor; Chemical and Biomolecular Separations, Supercritical Processing and Phase Equilibria, Lignin Separation and Purification

www.clemson.edu/ces/chbe/grad/prospectivegraduate/recruiting

Diana Stamey—Graduate Program Administrator chegrad@clemson.edu (864)-656-1182
We are a world-class department with 27 faculty (including 1 joint with chemistry), 39 postdoctoral fellows and research technicians, 128 graduate students, and more than 600 undergraduate students. Our research program is extremely active, including research centers in biorefining and biofuels, membranes, pharmaceutical biotechnology, and photopolymerization. Our department has many collaborations with nearby federal agencies such as NREL, NIST, NCAR and NOAA. Our department faculty have received national and international awards including the NSF Waterman Award, the AIChE R. H. Wilhelm Award, the AIChE Professional Progress Award, the AIChE Allan P. Colburn Award, the ASEE Curtis W. McGraw Award, and the ASEE Dow Lectureship Award. Our strong graduate program emphasizes the PhD degree and attracts outstanding national and international students. ChBE provides a 12-month stipend and tuition waivers for full-time Ph.D. students.

Located in Boulder, Colorado, CU-Boulder is nestled against the Rocky Mountains 25 miles northwest of Denver and less than 80 miles from world renowned skiing. Boulder enjoys over 300 days of sunshine per year allowing for a variety of outdoor activities including hiking, biking, skiing, rock climbing, and much more!
Evolving from its origins as a school of mining founded in 1873, CSM is a unique, highly-focused University dedicated to scholarship and research in earth, energy, and the environment. With approximately 650 total undergraduate and graduate students and $7-8 million in annual research funding, the Chemical and Biological Engineering Department at CSM maintains a high-quality and dynamic program. Research funding sources include federal agencies such as the NSF, DOE, DARPA, ONR, NREL, NIST, NIH as well as multiple industries. Our research areas include:

**MATERIAL SCIENCE AND ENGINEERING**
- Organic and inorganic membranes (Way, Herring)
- Polymeric materials (Dorgan, D.T. Wu, Liberatore)
- Colloids and complex fluids (Marr, D.T. Wu, Liberatore, N. Wu)
- Electronic materials (Wolden, Agarwal)
- Molecular simulation and modeling (D.T. Wu, Sum, Maupin)

**BIOMEDICAL AND BIOPHYSICS RESEARCH**
- Microfluidics/Biotransport (Marr, Neeves)
- Biological membranes (Sum)
- Metabolic engineering (Boyle)
- Drug delivery/Tissue engineering (Krebs, Neeves)
- Biosensors (Cash)

**ENERGY RESEARCH**
- Catalysts and kinetics (Carreon, Dean, Herring)
- CO₂ capture (Carreon, Way)
- H₂ separation and fuel cell membranes (Way, Herring)
- Natural gas hydrates (Sloan, Koh, Sum)
- Biofuels: Biochemical and thermochemical routes (Liberatore, Herring, Dean, Maupin)

Located at the foot of the Rocky Mountains less than 60 miles from world-class skiing and only 15 miles from downtown Denver, Golden, Colorado enjoys over 300 days of sunshine per year. These factors combine to provide year-round cultural, recreational, and entertainment opportunities virtually unmatched anywhere in the United States.

For more information contact Deanna Jacobs at 303-273-3720 or djacobs@mines.edu
http://chemeng.mines.edu
Research Areas
Systems and Synthetic Biology
Sustainable Energy
Biomedical Engineering
Soft Materials
Bioanalytical Devices

Faculty
Travis S. Bailey, Ph.D., U. Minnesota
Laurence A. Belfiore, Ph.D., U. Wisconsin
David S. Dandy, Ph.D., Caltech
J.D. (Nick) Fisk, Ph.D., U. Wisconsin
Matt J. Kipper, Ph.D., Iowa State U.
Brian Munskey Ph.D., U. California,
Santa Barbara
Christie Peebles, Ph.D., Rice U.
Ashok Prasad, Ph.D., Brandeis U.
Kenneth F. Reardon, Ph.D., Caltech
Brad Reisfeld, Ph.D., Northwestern U.
Christopher D. Snow. Ph.D., Stanford U.
Qiang (David) Wang, Ph.D., U. Wisconsin
A. Ted Watson, Ph.D., Caltech

Research
The graduate program in the Department of Chemical and Biological Engineering at Colorado State University offers students a broad range of cutting-edge research areas led by faculty who are world renowned experts in their respective fields. Opportunities for collaboration with many other department across the University are abundant, including departments in the Colleges of Engineering, Natural Sciences, and Veterinary Medicine and Biomedical Sciences.

Financial Support
Research Assistantships pay a competitive stipend. Students on assistantships also receive tuition support. The department has a number of research assistantships. Students select research projects in their area of interest from which a thesis or dissertation may be developed. Additional University fellowship awards are available to outstanding applicants.

Fort Collins
Located in Fort Collins, Colorado State is perfectly positioned as a gateway to the Rocky Mountains. With its superb climate (over 300 days of sunshine per year), there are exceptional opportunities for outdoor pursuits including hiking, biking, skiing, and rafting.

For additional information or to schedule a visit of campus:
Department of Chemical and Biological Engineering
Colorado State University
Fort Collins, CO 80523-1370
Phone: (970) 491-5253; Fax: (970) 491-7369
E-mail: cbe_grad@colostate.edu
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK
Graduate Programs in Chemical Engineering
M.S. and PhD Programs

--- Faculty and Research Areas ---

S. BANTA  Protein & Metabolic Engineering
C.J. DURNING  Polymer Physical Chemistry
D. ESPOSITO  Solar & Electrochemical Energy Conversion
G. FLYNN  Physical Chemistry
J. JU  Genomics
J. KOBERSTEIN  Polymers, Biomaterials, Surfaces, Membranes
S.K. KUMAR  Synthetic & Natural Polymers, Nanomaterials
E.F. LEONARD  Biomedical Engineering, Transport Phenomena
V. FAYE McNelll  Environmental Chemical Engineering,
                 Atmospheric Chemistry, Aerosols Molecular
V. ORTIZ  Modeling, Thermodynamics & Statistical Mechanics in Biology
B. O'SHAUGHNESSY  Polymer Physics
A.-H. ALISSA PARK  Sustainable Energy, Carbon Capture & Storage, Particle Technology
V. VENKATASUBRANIAN  Engineering, Systemic Risks Management,
                       Materials Design, Informatics & Artificial Intelligence
A.C. WEST  Electrochemical Engineering

Financial Assistance is Available

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WWW.CHEME.COLUMBIA.EDU
The Chemical & Biomolecular Engineering Program at UConn provides students with a thorough grounding in fundamental chemical engineering principles while offering opportunities and resources to specialize in a wide variety of focus areas.

Faculty

George Bollas, Ph.D.
Simulation of Energy Processes, Property Models Development

Kelly Burke, Ph.D.
Natural and Synthetic Biomaterials

Daniel Burkey, Ph.D.
Chemical Vapor Deposition, Engineering Pedagogy

C. Barry Carter, D. Phil, Sc.D.
Interfaces and Defects, Ceramics, Materials, TEM, SEM, AFM, Energy

Yongku Cho, Ph.D.
Protein Engineering, Optogenetics, Neuroimaging, Molecular Neurobiology

Douglas Cooper, Ph.D.
Process Modeling and Control

Cato Laurencin, Ph.D., M.D.
Advance Biomaterials, Tissue Engineering, Biodegradable Polymers, Nanotechnology

Yu Lei, Ph.D.
Bio-nanotechnology, Bio-nanosensors, Bi-nanomaterials, Remediation

Anson Ma, Ph.D.
Nanotechnology, Rheology, Emulsions and Foams, Inkjet and 3-D Printing

Radenka Marie, Ph.D.
Novel Materials for Energy Conversion and Storage, Biosensors, Coatings

Jeffrey McCutcheon, Ph.D.
Desalination, Water Treatment and Reuse, Polymer Electrospinning, Forward Osmosis

William Mustain, Ph.D.
Electrocatalysis, Batteries, Fuel Cells, Electrochemical Synthesis

Mu-Ping Nieh, Ph.D.
Structural Characterization of Soft Materials, Design of Self-Assembled Materials, Biomembranes

Richard Parnas, Ph.D.
Biodiesel Power Generation, PEM Fuel Cells, Polymer Gels, and Filled Polymers

Leslie Shor, Ph.D.
Biotechnology, Microfluidics, Microbial Assay Systems

Ranjan Srivastava, Ph.D.
Systems Biology and Metabolic Engineering

Luyi Sun, Ph.D.
Composite and Polymer Processing, Energy Conversion and Storage

Julia Valla, Ph.D.
Advanced Fuels Processing, Nanomaterials for Catalytic and Adsorption Processes

Kristina Wagstrom, Ph.D.
Atmospheric Chemistry, Air Pollution Modeling

Brian Willis, Ph.D.
Nanotechnology, Thin Films, Atomic Layer Deposition, Chemical Sensors

Research Centers

- Booth Engineering Center for Advanced Technologies
- Center for Clean Energy Engineering
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- Institute of Materials Science

Contact Information

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Research Areas

- Biomolecular, Cellular, and Protein Engineering
- Catalysis and Energy
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V. Kishore, Ph.D.

Research Interests
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CONTACT
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FACULTY

Rohit Bhargava (Biomedical Image Processing)
Ying Diao (Interfacial Phenomenon, Molecular Assembly for Energy and Healthcare)
Andrew L. Ferguson (Materials Science, Molecular Simulation, Bioinformatics)
David W. Flaherty (Catalysis, Surface Science and Materials Synthesis)
Damien S. Guironnet (Polymer Synthesis, Organometallic Chemistry and Catalysis)
William S. Hammack (Public Outreach and Engineering Literacy)
Brendan A. Harley (Biomaterials and Tissue Engineering)
Jonathan J. L. Higdon (Fluid Mechanics and Computational Algorithms)
Paul J. A. Kenis (Microchemical Systems: Microreactors, Microfuel Cells, and Microfluidics)
Hyun Joon Kong (Design of Bioinspired Materials, Stem Cell Niche, and Tissue Engineering)
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Deborah E. Leckband (Bioengineering and Biophysics)
Christopher V. Rao (Computational Biology and Cellular Engineering)
Charles M. Schroeder (Single Molecule Biology, Biophysics and Biomolecular Engineering)
Kenneth S. Schweizer (Macromolecular, Colloidal and Complex Fluid Theory)
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Diwakar Shukla (Molecular Engineering, Molecular Modeling and Simulations, Biophysics)
Charles E. Sing (Theoretical Polymer Physics, Statistical Mechanics, and Computer Simulation)
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- Nanotechnology

**Biological Engineering**
- Molecular Modeling Diabetes
- Biomedical and Pharmaceutical Engineering

**Systems Engineering**
- Complex Systems
- Advanced Process Control
- Process Modeling

**Faculty Research Interests**

**Javad Abbassian**
(Illinois Institute of Technology)
Coal gasification, high-temperature gas cleaning and process development

**Ali Cinar**
(Texas A&M)
Modeling, analysis and control of complex distributed systems, batch process supervision

**Satish Parulekar**
(Purdue University)
Chemical and biochemical reaction engineering

**Vijay Ramani**
(University of Connecticut)
Electrochemistry, fuel cell materials

**David C. Venerus**
(Penn State University)
Transport phenomena in complex materials, polymer rheology and processing

**Hamid Arastoopour**
(Illinois Institute of Technology)
Computational fluid dynamics of multiphase systems, nanoparticle fluidization

**John Anderson**
(University of Illinois)
Electrokinetic phenomena, electrophoresis of complex particles, transport in porous media and gels

**Nancy Karuri**
(University of Wisconsin)
Extracellular matrix interactions, interfacial chemistry

**Victor Perez-Luna**
(University of Washington)
Surface chemistry, biomaterials, biosensors, hydrogels, nanotechnology

**Joy D. Schieber**
(University of Wisconsin)
Multiscale modeling of macromolecule, transport phenomena, statistical mechanics

**Darsh T. Wasan**
(University of California, Berkeley)
Interfacial phenomena, wetting and spreading, nanofluids, food colloids

**Donald Chmielewski**
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Design and control of energy systems

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Background image: A microscopic image of a material in the lungs that aids in respiration captured while it is under stress earned first place for Investigator Prajna Dhar’s research group in the Biophysical Society’s Art of Science Image Contest.

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heterogeneous and environmental catalysis • shale gas and biomass conversion

Bryan W. Berger, Univ. of Delaware
membrane biophysics • protein engineering • surfactant science • signal transduction

Angela C. Brown, Drexel University
biological colloids • lipid-protein interactions • membrane biophysics • microbial pathogenesis

Javier Buceta, University of Madrid
cell/tissue biomechanics colloids • systems biology • biological stochasticity • multicellular systems modeling

Angela C. Brown, Drexel University
biochemical engineering

Hugo S. Caram, Univ. of Minnesota
high temperature processes and materials • environmental processes • reaction engineering

Manoj K. Chaudhury, SUNY - Buffalo
adhesion • thin films • surface chemistry

Mohamed S. El-Aasser, McGill U.
polymer colloids and films • emulsion copolymerization • polymer synthesis and characterization

James F. Gilchrist, Northwestern U.
particle self-organization • mixing • microfluidics, rheology

Lori Herz, Rutgers University
cell culture and fermentation • pharmaceutical process development and manufacturing

James T. Hsu, Northwestern U.
bioseparation • applied recombinant DNA technology

Anand Jagota, Cornell University
biomimetics • mechanics • adhesion • biomolecule-materials interactions

Andrew Kleins, North Carolina State U.
emulsion polymerization • colloidal and surface effects in polymerization

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catalyst materials • nanoparticle self-assembly • carbonaceous materials • heteroepitaxial interface structures

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Process modeling and control • microchemical systems • neuroengineering control

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process design and control • distillation

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polymer rheology and rheo-optics • polymer processing and modeling • membrane formation • drug delivery

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fuel cells • solid state ionics • heterogeneous catalysis • functional materials • electrochemistry

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protein folding • macromolecular crowding • hydrophobic effects • nanoscale transport

Jeevan Mittal, University of Texas
protein folding • macromolecular crowding • hydrophobic effects • nanoscale transport

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cell adhesion and migration • cellular biomechanics

Kelly M. Schultz, University of Delaware
polymer rheology and microchemistry • bio-compatible hydrogel characterization • three-dimensional cell culture

Arup K. Sengupta, University of Houston
use of adsorbents • sonication • reactive polymers • membranes in environmental pollution

Cesar A. Silebi, University of Houston
separation of colloidal particles • electroosmosis • mass transfer

Mark A. Snyder, University of Pennsylvania
adsorption • gas and liquid separation

Sivajy Sircar, University of Pennsylvania
material characterization • surface chemistry • heterogeneous catalysis • environmental catalysis

Kemal Tuzla, Istanbul Technical U.
heat transfer • two-phase flows • fluidization • thermal energy storage

Israel E. Wachs, Stanford University
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FACULTY:
BAYLES, TARYN, Ph.D., University of Pittsburgh; Engineering education, K-12 engineering curriculum development, teacher training
BLANEY, LEE, Ph.D., University of Texas at Austin; Water/wastewater treatment, pharmaceuticals and personal care products
CASTELLANOS, MARIAJOSÉ, Ph.D., Cornell University; Systems biology, engineering education
ENSEZER, JOSHUA, Ph.D., University of Notre Dame; Engineering education
FREY, DOUGLAS, Ph.D., University of California, Berkeley; Bioseparations, Chromatography
GOOD, THERESA, Ph.D., University of New York at Buffalo; Fate and transport of toxic organic compounds, remediation of sediments
GOOS, UDONG, Ph.D., UMBC; Sensor development
HENNIGAN, CHRISTOPHER, Ph.D., Georgia Institute of Technology; Air pollution chemistry, atmospheric aerosols
LEACH, JENNIE, Ph.D., University of Wisconsin - Madison; Protein aggregation and disease, cellular engineering
LISK, WALTER, Ph.D., University of Washington; Biosensor development
MOREIRA, ANTONIO, Ph.D., University of Pennsylvania; Fermentation, cell culture, regulatory science
PECHT, LAURA, Ph.D., National Institute of Standards and Technology; Nanotechnology, nanoengineering
RAGHUNATHAN, SARATH, Ph.D., UMBC; Sensors and bioelectronics
REED, BRIAN, Ph.D., University of New York at Buffalo; Fluorescence based sensors, instrumentation development, biomaterials
SHEPP, MICHAEL, Ph.D., UMBC; Proteomics, protein engineering, biomedical diagnostics
TOLOSA CROUCHER, LEAH, Ph.D., University of Connecticut, Storrs; Fluorescence based sensors, protein engineering, biomedical diagnostics, molecular switches
WITTMAN, BRAD, Ph.D., UMBC; Chemical engineering education

CONTACT:
Graduate Program Director
UMBC Chemical, Biochemical and Environmental Engineering
1000 Hilltop Circle, ENG 314
Baltimore, MD 21250
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SHERYL H. EHRMAN, CHAIR
Aerosol science, particle technology, air pollution.

RAYMOND A. ADOMAITIS
Systems modeling/simulation, semiconductor materials manufacturing.

MIKHAIL ANISIMOV
Mesoscopic and nanoscale thermodynamics, critical phenomena, phase transitions in soft matter.

RICHARD V. CALABRESE
Multiphase flow, turbulence and mixing.

KYU YONG CHOI
Polymer reaction engineering and polymer nanomaterials.

PANAGIOTIS DIMITRAKOPOULOS
Computational fluid dynamics, bio/microfluidics, biophysics and numerical analysis.

AMY J. KARLSSON
Protein engineering, biomolecular recognition, fungal disease.

JEFFERY KLAUDA
Cell membrane biophysics, thermodynamics, molecular simulations.

DONGXIA LIU
Materials synthesis and engineering, reaction engineering, heterogeneous catalysis, fuel cells, biofuels, energy.

SRINIVASA R. RAGHAVAN
Complex fluids, polymeric and biomolecular self-assembly, soft nanostructures.

GANESH SRIRAM
Systems biology, metabolic engineering, biorenewable fuel, genetically inherited metabolic disorders.

ERIC D. WACHSMAN
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University of Massachusetts
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Current Ph.D. projects receive support at a level of over $5 million per year through external research grants. Examples of research areas include:

- Bioengineering: cellular engineering; metabolic engineering; targeted bacteriolytic cancer therapy; synthesis of small molecules; systems biology; biopolymers; nanostructured materials for clinical diagnostics.

- Biofuels and Sustainable Energy: conversion of biomass to fuels and chemicals; catalytic fast pyrolysis of biomass; microkinetics; microwave reaction engineering; biorefining; high-throughput testing; reactor design and optimization; fuel cells; energy engineering.

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- Materials Science and Engineering: design and characterization of new catalytic materials; nanostructured materials for nanoelectronics, optoelectronics, and photovoltaics; graphene and carbon nanomaterials; synthesis and characterization of microporous and mesoporous materials; colloids and biomaterials; membranes; biopolymers; rheology and phase behavior of associative polymer solutions; polymeric materials processing.

- Molecular and Multi-scale Modeling & Simulation: computational quantum chemistry and kinetics; molecular modeling of nanostructured materials; molecular-level behavior of fluids confined in porous materials; molecular-to-reactor scale modeling of transport and reaction processes in materials synthesis; atomistic-to-continuum scale modeling of thin films and nanostructures; systems-level analysis using stochastic atomic-scale simulators; modeling and control of biochemical reactors; nonlinear process control theory.

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CHEMICAL AND BIOCHEMICAL ENGINEERING FACULTY AND RESEARCH INTERESTS

Muthanna Al-Dahhan (Professor and Chair), D.Sc., Washington University, St. Louis
Multiphase Reaction Engineering; Energy & Environmental Processes; Advanced Measurement & Computational Techniques

Baojun Bai (Associate Professor Joint Appointment with Petroleum Engineering), PhD, New Mexico Institute of Mining
Enhanced Oil Recovery Target, Conformance Control, Surfactants, Biosurfactants, Carbon Sequestration

Dipak Barua (Assistant Professor), PhD, North Carolina State University
Computational Systems Biology, Cell Singling Systems

Sutapa Barua (Assistant Professor), PhD, Arizona State University
Nanoparticles for Uniform Drug Delivery, Early Detection of Cancer Cells, Treatment of Devastating Diseases

Hank Foley (Joint Appointment, University of Missouri-Columbia), PhD, Penn State University
Catalysis and Reaction Engineering

Daniel Forciniti (Professor), PhD, North Carolina State University
Bioseparations; Thermodynamics; Statistical Mechanics

Chang-Soo Kim (Associate Professor Joint Appointment with Electrical Engineering & Biological Sciences)
PhD, Kyungpook National University
Functional Integration and Structural Integration of Advanced Microsystems, Biosensors

Xinhua Liang (Assistant Professor), PhD, University of Colorado
Surface Science; Nanostructured Films & Devices; Catalysis & Reaction Engineering; Energy & Environmental Applications

Athanasios I. Liapis (Professor), PhD, ETH-Zurich
Transport Phenomena; Adsorption; Bioseparations; Chromatography and Electrophorography; Chemical Reaction Engineering

Christi Patton Luks (Associate Teaching Professor), PhD, University of Tulsa
Engineering Education Pedagogy, Sustainable Engineering

Douglas K. Ludlow (Professor), PhD, Arizona State University
Surface Characterization of Adsorbents & Catalysts; Applications of Fractal Geometry to Surface Morphology

Parthasakha Neogi (Professor), PhD, Carnegie-Mellon University
Interfacial and Transport Phenomena

Joontaek Park (Assistant Professor), PhD, University of Florida
Dynamics & Rheology of Complex Fluids / Soft Matters

Fatemeh Rezaei (Assistant Professor), PhD, Monash University – Melbourne, Australia

Ali Rownaghi (Assistant Research Professor), PhD, University Putra - Malaysia
Sustainable Energy; Catalysis, Separations

Oliver C. Sitton (Associate Professor), PhD, Missouri S&T
Bioengineering

Joseph D. Smith (Lauffer Endowed Energy Chair Professor), PhD, Brigham Young University
Multiphase Reacting Flows; Catalysis; Dynamic Simulation; Coal/Biomass Gasification

Jee-Ching Wang (Associate Professor), PhD, Penn State University
Molecular Simulations of Transport in Confined Systems; Molecular Properties of Materials

David Westenberg (Associate Professor Joint Appointment with Biological Sciences), PhD, University of CA - Los Angeles
Molecular Microbiology, Microbial Diversity, Microbial Physiology

Yangchuan Xing (Adjunct Associate Professor, University of Missouri-Columbia), PhD, Yale University
Synthesis, Processing & Characterization of Nanomaterials

Silviya Petrova Zustiak (Joint Appointment with St. Louis University), PhD, University of Maryland Baltimore County
Tissue Engineering, Synthetic Biomaterials

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The Department of Chemical Engineering at UNH is located in the recently renovated Kingsbury Hall with state-of-the-art facilities in Biocatalysis, Biomaterials, Biomedical Engineering, Diagnostic Sensors, Electrochemical Engineering, Fuel Cells and Nanomaterials, Interfacial Flows, Molecular Simulations, Surface Chemistry, and Synthetic Biology. We offer PhD, MS, and MEng degrees in Chemical Engineering. All of our doctoral students are fully supported by teaching or research assistantships. UNH is located in Durham, NH 60 miles north of Boston, 14 miles from the Atlantic coast, and is conveniently located near New Hampshire’s lakes and mountains.

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Russell T. Carr
Non-linear Dynamics, Blood Rheology, Microfluidics

Nivedita R. Gupta
Computational Fluid Dynamics, Encapsulation, Interfacial Flows

Jeffrey M. Halpern
Diagnostic Sensors, Surface Chemistry, Sensor Development, Electrochemistry

Kyung Jae Jeong
Biomaterials and Surface Chemistry for Tissue Engineering

Xiaowei Teng
Nanomaterials, Fuel Cells, Supercapacitors, Reaction Engineering

Harish Vashisth
Computational Biophysics, Biomolecular Simulations of Proteins and Nucleic Acids

P. T. Vasudevan
Biocatalysis, Biofuels, Bioengineering

Kang Wu
Synthetic Biology, Protein Secretion, Biofuels, Bioremediation
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K. Hyun: University of Missouri-Columbia
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- **Shuguang Deng**, Professor (University of Cincinnati) Advanced Materials for Sustainable Energy and Clean Water, Adsorption, and Membrane Separation Processes
- **Reza Foudazi**, Assistant Professor (Capetown Peninsula University of Technology, South Africa) Porous Polymers, Rheology of Complex Fluids, Physicochemical Properties of Soft Matter, Colloid and Interface Science
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- **Hongmei Luo**, Associate Professor (Tulane University) Electrodeposition, Nanostructured Materials, Metal Oxide, Nitride, Composite Thin Films, Magnetism, Photocatalysts and Photovoltaics
- **Thomas A. Manz**, Assistant Professor (Purdue University) Computational Chemistry Study of Advanced Materials and Transition Metal Catalysts
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Research Areas
Bioengineering/Biomedical Engineering
Genetic engineering, protein production, bioseparations, metabolic engineering, biological transport, cancer treatment, cell adhesion, biosensors, orthopedic tissue engineering.

Energy and Chemicals
Biofuels and catalytic biomass conversion, catalytic hydrocarbon processing, plasma processing, data reconciliation, process design retrofit and optimization, molecular thermodynamics, computational modeling of turbulent transport and reactive flows, detergency, improved oil recovery.

Materials Science and Engineering
Single wall carbon nanotube production and functionalization, surface characterization, polymer melt blowing, polymer characterization and structure-property relationships, polymer nanolayer formation and use, biomaterials.

Environmental Processes
Zero-discharge process engineering, soil and aquifer remediation, surfactant-based water decontamination, sustainable energy processes.

For detailed information, visit our Web site at: www.CBME.ou.edu

Faculty Members

Miguel J. Bagajewicz
Ph.D.
California Institute of Technology, 1987

Steven P. Crossley
Ph.D.
University of Oklahoma, 2009

Brian P. Grady
Ph.D.
University of Wisconsin-Madison, 1994

Roger G. Harrison, Jr.
Ph.D.
University of Wisconsin-Madison, 1975

Jeffrey H. Harwell
Ph.D.
University of Texas, Austin, 1983

Dr. Peter J. Heinzelman
Ph.D. MIT, 2006

Liangliang Huang
Ph.D.
North Carolina State University, 2012

Friederike C. Jentoft
Ph.D.
Ludwig-Maximilians-Universität München, Germany, 1994

Lance L. Lobban
Ph.D. University of Houston, 1987

M. Ulli Nollert
Ph.D.
Cornell University, 1987

Dimitrios V. Papavassiliou
Ph.D.
University of Illinois at Urbana-Champaign, 1996

Daniel E. Resasco
Ph.D.
Yale University, 1983

Robert L. Shambaugh
Ph.D.
Case Western Reserve University, 1976

Vassilios I. Sikavitsas
Ph.D.
University of Buffalo, 2000

Bin Wang
Ph.D.
Ecole Normale Supérieure de Lyon, France 2010

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Vol. 48, No. 4, Fall 2014
Oklahoma State University
School of Chemical Engineering
M.S. and Ph.D. Programs

Faculty

Research Areas

Biomaterials
Ceramics
Colloids
Nanomaterials
Polymers
Biofuels
Gas Treating
Molecular Design
Petroleum
CO₂ Sequestrations

Advanced Materials
Biochemical Process
Disease Models
Drug Delivery
Gene Delivery
Tissue Engineering

Biomedical Engineering
Automation
Modeling / Simulation
Optimization
Separation Processes
Sustainability

Systems Engineering

Energy

For detailed information, visit:
http://che.okstate.edu/

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OFFERING MENG, MS AND PHD DEGREE PROGRAMS

Oregon State University (OSU) is a leading research university located in one of the safest, smartest and greenest cities in the nation. OSU holds the Carnegie Foundation’s top designation for research institutions. The School of Chemical, Biological and Environmental Engineering (CBEE) is one of four schools within the College of Engineering at OSU providing MEng, MS and PhD degrees in both Chemical and Environmental Engineering.

FACULTY

Liney Arnadottir U of Washington
Joseph Baio U of Washington
Michelle Bothwell Cornell
Chih-hung Chang U of Florida
Mark Dolan Stanford
Stacey Harper U of Nevada
Greg Herman U of Hawaii
Adam Higgins Georgia Tech
Goran Jovanovic Oregon State
Christine Kelly U of Tennessee
Milo Koretsky UC Berkeley
Keith Levien U of WI Madison
Joe McGuire NC State U
Devin Montfort Washington State
Jeff Nason U of Texas
Tyler Radniecki Yale
Skip Rochefort UC San Diego
Greg Rorrer Michigan State
Karl Schilke Oregon State
Lew Semprini Stanford
Travis Walker Stanford
D. Wildenschild Tech U Denmark
Brian Wood UC Davis
Alex Yokochi Texas A&M

RESEARCH

BIOREMEDIATION
BIOPROCESS ENGINEERING
BIOMATERIALS AND THERAPEUTICS
COMPLEX FLUIDS & NON-NEWTONIAN FLOW
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MICROTECHNOLOGY FOR REACTION AND SEPARATION PROCESSES
POLYMERS
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SUSTAINABLE ENERGY - RENEWABLE FUELS, SOLAR PV, ENERGY STORAGE
THIN FILMS, NANOMATERIALS AND NANOTECHNOLOGY
WATER QUALITY AND TREATMENT

For more information regarding our CBEE@oregonstate.edu school, call, email or visit us online: CBEE@OREGONSTATE.EDU

541-737-2491
FACULTY:

Paulo E. Arratia Biomechanics, fluid mechanics, mechanics of materials, complex and biofluid dynamics, multiphase flows

Tobias Baumgart Physical chemistry and mechanics of biological membranes, cell/surface interactions

Sue Ann Bidstrup Allen Polymeric and electronic materials, Electronic packaging and interconnection, high performance batteries

Russell J. Composto Polymeric materials science, surface and interface studies

John C. Crocker Single-molecule biophysics, cell mechanics, soft glasses

Scott L. Diamond Protein and gene delivery, mechano-biology, blood systems biology, drug discovery

Dennis E. Discher Polymersomes, protein folding, stem cell rheology, gene and drug delivery

Eduardo D. Glandt Classical and statistical thermodynamics, random media

Raymond J. Gorte Heterogeneous catalysis, supported metals, oxide catalysis, electrodes for solid-oxide fuel cells

Daniel A. Hammer Cellular bioengineering, biointerfacial phenomena, adhesion

Matthew J. Lazzara Cellular engineering, cell signaling, molecular therapeutics

Daeyeon Lee Surface and interface science; polymer/nanoparticle thin films; microfluidics; emulsion science; stimuli-responsive microcapsules, soft matter

Amish J. Patel Biological self-assembly, desalination, solvation in nano-confined geometries, li-ion batteries, nano-structured polymers

Ravi Radhakrishnan Statistical mechanics, quantum chemistry, biomolecular and cellular signaling

Robert A. Riggleman Molecular modeling, statistical mechanics, and polymer glasses

Warren D. Seider Process analysis, simulation, design, and control

Wen K. Shieh Bioenvironmental engineering, environmental systems modeling

Talid R. Sinno Transport and reaction, statistical mechanical modeling

Kathleen J. Stebe Nanomaterials, surfaces and interfaces, dynamics of self assembly, surfactants

John M. Voigt Surface science, catalysis, electronic materials processing

Karen I. Winey Polymer morphology, processing, and property interrelationships

Shu Yang Synthesis, characterization and fabrication of functional polymers, and organic/inorganic hybrids

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The Department of Chemical Engineering at The Pennsylvania State University has a proud tradition of scholarship and teaching that began with Professor Merrell Fenske, the first Head of our Department and a pioneer in the technology of distillation. Our department is one of the finest Chemical Engineering programs in the country and offers cutting-edge research areas of chemical engineering. Opportunities for collaboration with other departments and institutes across the University are abundant. Research assistantships and fellowships pay a competitive stipend, health insurance as well as tuitions. Additional University fellowship awards are available to outstanding applicants.
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FACULTY AND RESEARCH AREAS IN THE DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING AT PITT:

Mohammad Ataai
biotechnology, biomolecular engineering

Anna C. Balazs
theory, computational modeling, polymers, composites

Ipsita Banerjee
bioengineering, systems biology, regenerative medicine

Eric Beckman
sustainability, polymers

Cheryl Bodnar
games, engineering education, innovative design, entrepreneurial mindset

Andrew Banger
hydraulic fracturing, geological engineering

Julie d'Itri
catalysis, chemical kinetics, characterization

Robert M. Enick
petroleum engineering, CO₂ solubility, carbon capture, high pressure phase behavior

Di Gao
nanomaterials, surface science

J. Karl Johnson
computational modeling, nanoporous materials, CO₂ capture and reduction, energy storage

John A. Keith
computational modeling, catalysis, photoelectrochemistry, renewable energy

George E. Klinzing
pneumatic conveying, dense phase transport, dense phase flow simulations

Prashant N. Kumta
energy storage, biomaterials

Lei Li
surface science, ionic liquids, wetting, tribology

Steven R. Little
drug delivery, biomaterials, immunengineering, regenerative medicine

Joseph J. McCarthy
particulates, cohesive materials, heat transfer, transport

Badie I. Morsi
petroleum engineering, reactors, processes, carbon capture and sequestration

Giannis Mpourmpakis
computational modeling, catalysis, nanotechnology, renewable energy

Robert S. Parker
process control, systems medicine, nonlinear dynamical modeling

Sachin Velankar
rhelology, polymers, capillarity, colloids

Günter Vesztergombi
catalysis, process intensification, nanomaterials, nanotoxicity

Christopher Wilmer
computational modeling, data mining, renewable energy, hypothetical materials

Judith C. Yang
surface science, catalysis, nanomaterials, materials characterization

Financial assistance is available to those who qualify.
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Ph.D. and M.Eng. Programs in
Chemical and Biological Engineering

CBE Faculty

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Yueh-Lin (Lynn) Loo
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Athanassios Z. Panagiotopoulos
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Robert K. Prud’homme
Richard A. Register (Chair)
William B. Russel
Stanislav Y. Shvartsman
Sankaran Sundaresan

Affiliate Faculty

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George W. Scherer (Civil and Environmental Engineering)
Howard A. Stone (Mechanical and Aerospace Engineering)
Claire E. White (Civil and Environmental Engineering)

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From left: Arvind Varma, Head, Purdue School of Chemical Engineering; Leah Jamieson, Dean, Purdue College of Engineering; Sangtae Kim, Distinguished Professor; Mitch Daniels, President, Purdue University

Research Areas
Biochemical and Biomolecular Engineering
Biotechnology
Catalysis and Reaction Engineering
Electronics
Energy
Fluid Mechanics and Interfacial Phenomena
Homeland Security
Manufacturing
Mass Transfer and Separations
Molecular and Nanoscale Modeling
Nanoscale Science and Engineering
Pharmaceuticals
Polymers and Advanced Materials
Polymers and Materials
Product and Process Systems Engineering
Thermodynamics

Faculty
Rakesh Agrawal
Osman A. Basaran
Stephen P. Beaudoin
Bryan W. Boudouris
James M. Caruthers
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Elias I. Franses
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Michael T. Harris
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Zoltan K. Nagy
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R. Byron Pipes
Vilas G. Pol
Doraiswami Ramkrishna
Gintaras V. Reklaitis
Fabio H. Ribeiro
Kendall T. Thomson
Arvind Varma (Head)
Nien-Hwa L. Wang
Phillip C. Wankat
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Chemical & Biological Engineering

Rensselaer Polytechnic Institute

The Howard P. Isermann Department of Chemical and Biological Engineering has long been recognized for its excellence in teaching and research. Its graduate programs lead to research-based M.S. and Ph.D. degrees and to a course-based M.Eng degree. Programs are also offered in cooperation with the School of Management and Technology which lead to an M.S. in Chemical Engineering and an MBA or an M.S. in Management. Owing to its funding, consulting, and previous faculty experience, the department maintains close ties with industry. For more information, please visit our department website: http://cbe.rpi.edu

Rensselaer Polytechnic Institute is the oldest technological research university in the United States. Located in Troy, New York, Rensselaer is a private university with an enrollment of approximately 7,000 undergraduate and graduate students studying engineering, the sciences, information technology, architecture, management, humanities and the arts. Our faculty members include National Science Foundation Presidential Faculty Fellows, and members of the National Academy of Engineering and the National Academy of Sciences. Situated on the Hudson River, just north of New York's capital city of Albany, our campus is a three-hour drive from New York City, Boston, and Montreal. For application materials and additional information, please contact:

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Email: admissions@rpi.edu
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Emeritus Faculty

Henry R. Bungay III, bungah@rpi.edu
Wastewater treatment, biochemical engineering

Arthur Fontijn, fontia@rpi.edu
Combustion, high temperature kinetics, gas-phase reactions

Faculty and Research Interests

Georges Belfort, belfog@rpi.edu
Membrane separations; adsorption, bioconversion; MRI, interfacial phenomena

B. Wayne Bequette, bequette@rpi.edu
Process control; fuel cell systems; biomedical systems

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Semiconductor electronics, energy, advanced materials, optical and electronic properties of wide bandgap materials

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Systems biology; protein engineering; intercellular communication systems; synthetic microbial ecosystems

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Displacement, membrane and preparative chromatography; environmental research

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Biochemical engineering; biocatalysis; polymer science; bioseparations

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Macromolecular self-assembly, computer simulations, statistical thermodynamics of liquids, hydration phenomena

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Polymers; biosurfaces; biomaterials; nanomaterials, nanobiotechnology

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Drug delivery; combinatorial chemistry; molecular modeling; high throughput screening

Matthijs Koffas, koffam@rpi.edu
Metabolic engineering, natural products, drug discovery and biofuels

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Polymers, Nanoparticles, Nanotechnology, Self-assembly, Symmetries, Soft materials, Surfactants

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Electronic and photonic materials; interfacial phenomena; transport phenomena

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Protein-protein interactions, protein self-assembly and aggregation

Patrick T. Underhill, underhill@rpi.edu
Transport phenomena, multi-scale model development and applications to colloidal, polymer, and biological systems

William N. Gill, gilln@rpi.edu
Microelectronics; reverse osmosis; crystal growth; ceramic composites

Howard Littman, littmhb@rpi.edu
Fluid/particle systems; fluidization; spouting bed; pneumatic transport

Peter C. Wawer, Jr., wawer@rpi.edu
Heat transfer; interfacial phenomena; porous materials
THE UNIVERSITY

- Rice is a leading research university - small, private, and highly selective - distinguished by a collaborative, highly interdisciplinary culture.
- State-of-the-art laboratories, internationally renowned research centers, and one of the country's largest endowments support an ideal learning and living environment.
- Located only a few miles from downtown Houston, it occupies an architecturally distinctive, 300-acre campus shaded by nearly 4,000 trees.

THE DEPARTMENT

- Offers Ph.D., M.S., and M.Ch.E. degrees.
- Provides 12-month stipends and tuition waivers to full-time Ph.D. students.
- Currently has 80 graduate students (Fall 2013).
- Emphasizes interdisciplinary studies and collaborations with researchers from Rice and other institutions, national labs, the Texas Medical Center, NASA's Johnson Space Center, and R&D centers of petrochemical companies.

FACULTY RESEARCH AREAS

Advanced Materials and Complex Fluids
Synthesis and characterization of nanostructured materials, catalysis, nano- and microfluidics, self-assembling systems, hybrid biomaterials, rheology of nanostructured liquids, polymers, carbon nanotubes, interfacial phenomena, emulsions, and colloids.

Biosystems Engineering
Metabolic engineering, systems biology, nutritional systems biology, protein engineering, cellular and tissue engineering, microbial fermentations, analysis and design of gene networks, cellular reprogramming, and cell population heterogeneity.

Energy and Sustainability
Transport and thermodynamic properties of fluids, biofuels, CO2 sequestration, biochar, gas hydrates, enhanced oil recovery, reservoir characterization, and pollution control.

For more information and graduate program applications, write to: Chair, Graduate Admissions Committee
Chemical and Biomolecular Engineering, MS-362
Rice University, P.O. Box 1892
Houston, TX 77251-1892

Or visit our web site at http://www.rice.edu/chbe
The Chemical Engineering Department at The University of Rochester offers M.S. and Ph.D. programs designed to both challenge and support our students' learning. Our graduate programs are among the highest ranked in the nation according to a recent NRC survey*. We provide leading edge research opportunities that cut across the boundaries of chemistry, physics, biology and chemical engineering disciplines with emphasis in energy, materials and biotechnology research. For qualified students, we offer competitive teaching and research assistantships and tuition scholarships.

* 2010 National Research Council Report www.nap.edu/rpd/

M. ANTHAMATTEN
PhD MIT, 2001
macromolecular self-assembly, shape memory polymers, vapor deposition, fuel cells

D. BENOIT
PhD Colorado, 2006
nuclear design, synthesis, characterization, and employment of materials to treat diseases or control cell behavior

S. H. CHEN
PhD Minnesota, 1981
polymer science, organic materials for photonics and electronics, liquid crystal and electro- luminescent displays

E. H. CHIMOWITZ
PhD Connecticut, 1982
supercritical fluid adsorption, molecular simulation of transport in disordered media, statistical mechanics

D. R. HARDING
PhD Cambridge, 1986
chemical vapor deposition, mechanical and transport properties, advanced aerospace materials

S. D. JACOBS
PhD Rochester, 1975
optics, photonics, and optoelectronics, liquid crystals, magnetochemistry

J. JORNE
PhD UC Berkeley, 1972
electrochemical engineering, fuel cells, microelectronics processing, electrodeposition

H. MUKAIBO
PhD Waseda (Japan), 2006
materials science, bio/nanoscience, bio-analytical chemistry, electrochemistry, energy storage

L. J. ROTHBERG
PhD Harvard, 1984
organic device science, light-emitting diodes, display technology, biological sensors

C. W. TANG
PhD Cornell, 1975
organic electronic devices, solar cells, flat-panel display technology

A. SHESTOPALOV
PhD Duke, 2009
unconventional fabrication, patterning techniques, preparation of functional micro and nanostructured devices

Y. SHAPIR
PhD Tel Aviv (Israel), 1981
critical phenomena, transport in disordered media, scaling behavior of growing surfaces

A. WHITE
PhD Washington, 2013
computer simulation and data informatics design of materials for self-assembly, batteries and biomaterials

J. H. DAVID WU
PhD MIT, 1987
bone marrow tissue engineering, stem cell and lymphocyte cultures, enzymology of biomass energy process, bio-ethanol and bio-hydrogen

W. TENHAEFF
PhD MIT, 2009
electrochemical energy storage, solid state lithium batteries and solid electrolytes, polymer thin films, interfaces and thin film synthesis and characterization, vacuum deposition techniques

M. Z. YATES
PhD Texas, 1999
colloids and interfaces, supercritical fluids, microemulsions, molecular steels, fuel cells

Faculty

Advanced Materials
- Liquid Crystals
- Colloids & Surfactants
- Functional Polymers
- Inorganic/Organic Hybrids

Nanotechnology
- Thin Film Devices
- Photonics & Optoelectronics
- Nanofabrication
- Display Technologies

Clean Energy
- Fuel Cells & Batteries
- Solar Cells
- Biofuels
- Green Engineering

Biotechnology
- Biomass Conversion
- Stem Cell Engineering
- Drug Delivery
- Biosensing

Graduate Studies & Research Programs

Chemical Engineering Graduate Studies
http://www.che.rochester.edu

Department of Chemical Engineering
University of Rochester
206 Gavett Hall
Rochester, NY 14627
(585) 275-4513
The faculty at the University of Rochester have established strong research programs in advanced materials, biotechnology, and nanotechnology – the intellectual foundations for graduate education leading to Master's degrees. At the technological front, members of the Chemical Engineering faculty conduct research and teach courses highly relevant to alternative energy. Graduate-level courses and active research programs are underway in fuel cells, solar cells, and biofuels.

This program is designed for graduate students with a Bachelor's degree in engineering or science, who are interested in pursuing a technical career in alternative energy. Courses and research projects will focus on the fundamentals and applications of the generation, storage, and utilization of various forms of alternative energy as well as their impact on sustainability and energy conservation.

**FACULTY and RESEARCH PROGRAMS**

**Fundamentals**

- M. Anthamatten
  Ph.D., MIT, 2001
- S. H. Chen
  Ph.D., Minnesota, 1981
- E. H. Chimowitz
  Ph.D., Connecticut, 1982
- D. Foster
  Ph.D., Rochester, 1999
- T. D. Krauss
  Ph.D., Cornell, 1998

**Biofuels**

- J. H. David Wu
  Ph.D., MIT, 1987
- S. H. Chen
  Ph.D., Minnesota, 1981

**Nuclear Energy**

- W-U. Schröder
  Ph.D., Darmstadt, 1971

**Fuel Cells and Batteries**

- M. Anthamatten
  Ph.D., MIT, 2001
- J. Jorne
  Ph.D., California (Berkeley), 1972
- W. Tenhaff
  Ph.D., MIT, 2009
- M. Z. Yates
  Ph.D., Texas, 1999

**Solar Cells**

- S. H. Chen
  Ph.D., Minnesota, 1981
- T. D. Krauss
  Ph.D., Cornell, 1998
- C. W. Tang
  Ph.D., Cornell, 1975

Alternative Energy
University of Rochester
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http://www.che.rochester.edu/altenergy.htm
The Chemical Engineering Department at Rowan University offers a multidisciplinary research and teaching environment designed to help students achieve their full potential. State-of-the-art laboratories and classrooms, and an emphasis on project management and industrially-relevant research are the hallmarks of Rowan Chemical Engineering. The Department has access to Rowan’s two medical schools and the South Jersey Technology Center. In addition, the University has achieved New Jersey state research university designation. Rowan Chemical Engineering offers students an excellent education with numerous opportunities in emerging technologies.

Located in southern New Jersey, Rowan University is nestled between rural and major metropolitan areas. Philadelphia, the Jersey shore, orchards, and farms are all only a short drive away, and cultural and recreational opportunities are plentiful in the area.

**Faculty**

Kevin D. Dahm - Massachusetts Institute of Technology  
Stephanie Farrell - New Jersey Institute of Technology  
Zenaida Otero Gephardt - University of Delaware  
Robert P. Hesketh - University of Delaware  
Mariano J. Savelski, Chair - University of Oklahoma  
C. Stewart Slater - Rutgers University  
Mary M. Staehle - University of Delaware  
Joseph F. Stanzione, III - University of Delaware  
Jennifer Vernengo - Drexel University

**Research Areas**


**For additional information**

Dr. Joseph F. Stanzione, III - Department of Chemical Engineering  
Rowan University - 201 Mullica Hill Road - Glassboro, NJ 08028  
Phone: (856) 256-5310 - Fax: (856) 256-5242  
E-mail: stanzione@rowan.edu - Web: http://www.rowan.edu/engineering/
Chemical Engineering at Ryerson University

Ryerson University offers an excellent graduate education in the heart of the vibrant city of Toronto, Ontario, Canada. Ryerson offers more than 100 undergraduate and graduate programs.

The Department of Chemical Engineering offers a versatile and unique program leading to a doctor of philosophy (PhD) degree, a master of applied science (MASc) degree or a master of engineering (MEng) degree. The course-based MEng degree can be completed through either full- or part-time study, while the research-intensive thesis-based MASc and PhD degrees are offered through full-time study.

KEY RESEARCH AREAS

Water/Wastewater and Food Treatment Technologies
- Use of rotating biological contactors and three-phase fluidized beds in treatment of industrial and municipal effluents
- Photo-oxidation and ozone technology applied to treatment of water and wastewater
- Chemical engineering and biological processes
- Fundamental studies of adsorption and absorption of pollutants on solids and liquids
- Bio-adsorption of heavy metals and other contaminants
- Membrane process application in wastewater treatment, membrane fouling
- Biofuel ethanol: all processing steps to convert lignocellulosics into green ethanol
- Recombinant cellulases in transgenic plants
- Anaerobic digestion of agricultural food wastes
- Catalytic conversion of wastewater

Polymer and Process Engineering
- Polymer rheology and application to processing techniques
- Kinetics of polymerization
- Nonlinear optical polymers
- Kinetics of phase transition and phase separation in polymer solutions
- Computer simulation of phase separation in polymer systems
- Computer simulation of complex fluids/condensed soft matter
- Process control and optimization: chemical reactors and in-line (red) corrected dryer
- Liquid crystalline and rod polymers
- Chemical reaction engineering: supercritical fluids and phase equilibria
- Biopolymers and biomaterials
- Interfacial rheology and surface chemistry
- Emulsion stabilization with colloidal particles
- Process modeling and simulation: Artificial Neural Networks (ANN) design
- Microfluidics and nanotechnology and synthesis of advanced materials
- Mixing of fluids with complex rheology
- Flow visualization (tomography and ultrasonic velocimetry)
- Computational fluid mixing
- Non-Newtonian fluid dynamics
- Microporous and mesoporous materials: growth, synthesis, characterization, and surface chemistry
- Optimal control of chemical processes
- Mass transfer in polymer-solvent systems
- Oil/gas processing and production; SAGD, VAPEX, Hybrid and SA-SAGS processes
- Utilization of waste products: fly ash characterization and use; biofuel and energy from agricultural waste and industrial/forest by-products

FACULTY
- Manuel Alvarez-Cuenca (PhD, Western Ontario)
- Philip Chau (PhD, McGill)
- Chi-Hung Cheng (PhD, Texas A&M)
- Yaser Dahman (PhD, Western Ontario)
- Ramchand Dhib (PhD, Sherbrooke)
- Huu Doan (PhD, Toronto)
- Dae Jun Hwang (PhD, McGill)
- Ali Lohi (PhD, Waterloo)
- Mehrab Mehrvar (PhD, Waterloo)
- Farhad Ein-Mozaffari (PhD, British Columbia)
- Ginette Turcotte (PhD, Western Ontario)
- Simant Upreti (PhD, Calgary)
- Stephen Waldman (PhD, Dalhousie)
- Jiangning Wu (PhD, Windsor)

FOR MORE INFORMATION

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See our research teams revolutionizing the technology

Located 150 km east of Montreal, Sherbrooke is a university town of 150,000 inhabitants offering all the advantages of city life in a rural environment.

With strong ties to industry, the Department of Chemical and Biotechnological Engineering offers graduate programs leading to a master's degree (thesis and non-thesis) and a PhD degree.

Take advantage of our innovative teaching methods and close cooperation with industry!
As a Department that is recognized in the world, we offer a comprehensive selection of courses and activities for a distinctive and enriching learning experience. You will benefit from the opportunity to work with our diverse faculty in a cosmopolitan environment. Join us at NUS – Singapore’s Global University, and be a part of the future today!

Program Features
- Research activities in a broad spectrum of fundamental, applied and emerging technological areas
- Active research collaboration with the industry, national research centers and institutes
- Top-notch facilities for cutting-edge research under the supervision of world’s renowned researchers
- Strong international research collaboration with universities in America, Europe and Asia
- Over 150 research scholars (80% pursuing Ph.D.) from America, Europe, Middle East and Asia
- Financial assistance, scholarships, tuition fee waivers and awards available for application

Strategic Research & Educational Thrusts
- Biomolecular and Biomedical Engineering
- Chemical Engineering Sciences
- Chemical & BioSystems Engineering
- Environmentally Benign Processing & Sustainability
- Nanostructured and Functionalized Materials & Devices

International Rankings
Quacquarelli Symonds (QS) World University Rankings
✓ Ranked 1st in QS University Rankings: Asia 2014
✓ Ranked 5th in QS World University Rankings by Subjects

Times Higher Education (THE) World University Rankings
✓ Ranked 2nd in THE Asia University Rankings 2014
✓ Ranked 21st in THE World Reputation Rankings 2014

Strategic Research & Educational Thrusts
- Research-based
  - Ph.D. and M.Eng.
- Coursework-based
  - M.Sc. (Chemical Engineering)
  - M.Sc. (Safety, Health & Environmental Technology)

Our Graduate Programs
Research-based
Coursework-based

Engineer Your Own Evolution! Reach us at:

National University of Singapore
Department of Chemical & Biomolecular Engineering
4 Engineering Drive 4, #02-09 Singapore 117585
Email: chbe_grad_programs@nus.edu.sg • http://www.chbe.nus.edu.sg • Tel: +65 6516-5031
University of South Alabama
Chemical & Biomolecular Engineering

T. Grant Glover, Assistant Professor
Ph.D, Vanderbilt University
Multifunctional Nanoporous Materials

B. Keith Harrison, Professor and Assoc. VP
Ph.D, University of Missouri
Thermodynamics, Process Simulation

Silas J. Leavesley, Associate Professor
Ph.D, Purdue University
Biomedical Devices, Hyperspectral Imaging

Srinivas Palanki, Professor and Chair
Ph.D, University of Michigan
Alternative Energy, Systems Engineering

Nicholas D. Sylvester, Professor
Ph.D, Carnegie Mellon University
Microcontinuum Fluid Mechanics

Christy W. West, Assistant Professor
Ph.D, Georgia Institute of Technology
Chemical Reaction Systems, Catalysis

Kevin N. West, Associate Professor
Ph.D, Georgia Institute of Technology
Ionic Liquids, Molecular Thermodynamics

The department offers an M.S in Chemical Engineering and a D.Sc in Systems Engineering. Graduate students can also opt for the Biomedical Engineering track in the Basic Medical Sciences Ph.D program offered by the College of Medicine. The relatively small size of the graduate program promotes close interaction between students and faculty members. Current research is sponsored by NSF, NIH, NASA, DOD and chemical companies. Qualified students are offered competitive research and teaching assistantships. In 2012, the department moved to Shelby Hall, the new $40 million Engineering and Computing Building.

The department is located near the white sand beaches of the central gulf coast of the United States. There are a large number of local chemical and manufacturing industries such as Chevron, Evonik, Mitsubishi, AkzoNobel, BASF, Thyssen-Krupp, and Olin that provide employment opportunities to our graduates.
The Department of Chemical Engineering at USC has emerged as one of the top teaching and research programs in the Southeast. Our national rankings include a top 20 in research expenditures, a top 30 by the National Research Council (NRC), and a top 50 by US News & World Report. The Department offers ME, MS, and PhD degree programs in chemical engineering and biomedical engineering. PhD candidates receive tuition and fee waivers, a health insurance subsidy, and highly competitive stipends starting at $25,000 per year.

The University of South Carolina is located in Columbia, the state capital, which offers the benefits of a big city with the charm and hospitality of a small town. Charlotte and Atlanta, cities that serve as Columbia's international gateways, are nearby. The area's sunny and mild climate, combined with its lakes and wooded parks, provide plenty of opportunities for year-round outdoor recreation. In addition, Columbia is only hours away from the Blue Ridge Mountains and the Atlantic Coast.

Carolina's mascot, Cocky, shows off on one of our department's hydrogen fuel cell Segways at university events.

FACULTY

M. D. Amiridis, Wisconsin
Provost, Catalysis and Kinetics

F. A. Gadala-Maria, Stanford
Rheology of suspensions

E. P. Gatzke, Stanford
Modeling Control, Optimization

J. Hattrick-Simpers, Maryland
Membranes, Materials

A. Heyden, Hamburg
Computational Nanoscience, Catalysis

E. Jabbari, Purdue
Biomedical and Tissue Engineering

E. Jabbarzadeh, Drexel
Vascular and Cellular Engineering

J. A. Lauterbach, Berlin
Environmental Catalysis

M. A. Matthews, Texas A&M
Applied Thermodynamics, Supercritical Fluids

M. A. Moss, Kentucky
Protein Biophysics, Alzheimer's Disease

B. Padak, Stanford
Combustion and Emissions Control

H. J. Ploehn, Princeton
Interfacial Phenomena Polymer Nanotechnology

B. N. Popov, Zagreb, Croatia
Electrochemical Power Sources

J. R. Regalbuto, Notre Dame
Catalysis, Preparation and Characterization

J. A. Ritter, SUNY Buffalo
Adsortive Separations and Energy Storage

M. J. Uline, Purdue
Molecular Modeling, Biological Systems

J. W. Weidner, NC State
Electrochemical Engineering, Electrocatalysis

R. E. White, Cal-Berkeley
Electrochemical Engineering, Modelling

C. T. Williams, Purdue
Catalysis, Surface Spectroscopy

M. Yu, Colorado
Solar Energy Conversion, Membranes, Nanomaterials

X. D. Zhou, Missouri Rolla
Materials, Electrochemistry, Electrodes
Department of Chemical and Biological Engineering

- 2010 NRC rankings place UB CBE in 8th and 9th place for publications and awards per faculty, respectively, among 106 reviewed departments
- Outstanding funding from NIH, NYSTEM, NSF, USAF, AHA, DOE
- 7 NSF CAREER Awards
- 3 members of National Academy of Engineering

Bioengineering research
- Andreadis - Adult and induced pluripotent stem cells for cardiovascular tissue engineering, signaling pathways in cell-cell adhesion and wound healing, biomaterials for protein and gene delivery, lentiviral vectors and lentiviral microarrays for high-throughput gene expression analysis and gene discovery
- Neelamegham - Cell biomechanics, systems biology, thrombosis and hemostasis, glycosciences
- Park - Biotechnology, protein engineering, simulated dynamics, bioinformatics, drug discovery
- Pleifer - Metabolic engineering, heterologous natural product biosynthesis, genetic vaccine design

Modeling and computational research
- Errington - Molecular simulation, statistical thermodynamics, interface phenomena
- Furlani - Multidisciplinary modeling: microfluidics, computational fluid dynamics, mass/heat transfer, multiphase systems, MEMS, nanophotonics, biomagnetics
- Hachmann - Computational chemistry and materials science, virtual high-throughput and Big Data, machine learning, electronic structure theory and methods, quantum effects in catalysis and materials
- Koelle - Statistical physics, molecular modeling and simulation, software engineering
- Lockett - Mass/heat transfer, distillation, separations
- Nitsche - Transport phenomena, dermal absorption, biological membrane and pore permeability

Materials research
- Alexandridis - Self-assembly, directed assembly, complex fluids, soft materials, nanomaterials, interface phenomena, amphiphilic polymers, biopolymers, product design
- Cheng - Biodegradable functional polymers and nanostructures, new drug delivery systems, synthetic materials for tissue engineering
- Lin - Membrane materials and processes for gas and vapor separation and water purification
- Lund - Heterogeneous catalysis, chemical kinetics, reaction engineering
- Ruckenstein - Catalysis, surface phenomena, colloids and emulsions, biocompatible surfaces and materials
- Swihart - Synthesis and application of nanoparticles, reactor modeling, computational chemistry, particle nucleation and growth
- Tsianou - Molecularly engineered materials, self-assembly, interfacial phenomena, crystal engineering, bio-inspired materials
- Zukoski - Suspension mechanics, protein crystallization and nanoparticle self-assembly
Recent advances in the life sciences and nanotechnology, as well as the looming energy crisis, have brought chemical engineering education to the threshold of significant changes. The Department of Chemical and Biomolecular Engineering (CBE) at the University of Tennessee has embraced these changes in order to meet global challenges in health care, the environment, renewable energy sources, national security and economic prosperity. Partnerships with other disciplines at UT, such as medical, life, and physical sciences, as well as the College of Business Administration and Oak Ridge National Laboratory (ORNL), help to create exceptional research opportunities for graduate students in CBE and place our students in a position to develop leadership roles in the vital technologies of the future.

The UTK campus is located in the heart of Knoxville in beautiful east Tennessee, minutes from the Great Smoky Mountains National Park and surrounded by six lakes. Opportunities for outdoor recreation abound and are complemented by the diverse array of cultural activities afforded by our presence in the third largest city in Tennessee.

Chemical and Biomolecular Engineering at UT-Knoxville offers M.S. and Ph.D. degrees with financial assistance including full tuition and competitive stipends.

Chemical & Biomolecular Engineering
419 Dougherty Engineering Building
Knoxville, TN 37996-2200
Phone: (865) 974-2421
Email: cheinfo@utk.edu
Chemical Engineering at Tennessee Tech University

Pedro E. Arce, Professor and Chair
PhD, Purdue University, 1990.
Electrokinetics, Nano-Composite Soft Material for Electrophoresis (Environmental Proteomics, Clinical Diagnostics); Drug Delivery; Advanced Oxidation; Engineering Education.

Laura H. Arias-Chavez, Assistant Professor
PhD, Yale University, 2014
Polymer Membrane: Fabrication and Characterization; Drinking Water Treatment; Sustainable Energy Production; Nanofibers via Electro-Spinning.

Joseph J. Biernacki, Professor
DRE, Cleveland State University, 1988.
Cementitious Materials (Hydration Kinetics, Material Structure); Green Chemistry-based Biofuels; Multi-Scale Materials (Modeling and Properties); Engineering Education.

Bahman Ghorashi, University Provost
PhD, Ohio State University, 1980
Fluid Mechanics; Combustion; Agile Manufacturing; Management of Technology.

Laura H. Arias-Chavez, Assistant Professor
PhD, Yale University, 2014
Polymer Membrane: Fabrication and Characterization; Drinking Water Treatment; Sustainable Energy Production; Nanofibers via Electro-Spinning.

Yung-Way Lin*, Professor of Mathematics
PhD, University of Delaware, 1987.
Integral Boundary Methods; Dispersion Models in Capillaries; Applied Mathematics.

Jennifer Pascal, Assistant Professor
PhD, Tennessee Technology University, 2011
Drug Delivery to Tumors; Electrical Field-based Transport; Mathematical/Computational Modeling of Biological Systems; Engineering Education.

Jeffrey Rice, Assistant Professor
PhD, University of California, Santa Barbara, 2007

Cynthia Rice, Assistant Professor
PhD, University of Illinois, Urbana-Champaign, 2000.
Fuel Cells; Electrocatalysis, Research Methods in Undergraduate Education.

J. Robert Sanders, Assistant Professor
PhD, Vanderbilt University, 2001.
Biomolecular Medicine; Micro-fluidics in Clinical Diagnostics; Drug Delivery and Gene Therapy; Engineering Education.

Holly Stretz, Associate Professor
PhD, University of Texas, Austin, 2005.
Nanocomposite Structures and Modeling; High Temperature Materials and Ablatives; Polymer Processing.

Dr. Kenneth Wiant*, Professor of Finance, College of Business
PhD, University of South Carolina, 1991, Innovation in Educational Technology, Corporate Finance, International Corporate Finance
(*) Collaborating faculty

Students with backgrounds in engineering (e.g., Chemical, Biomedical, Environmental, Mechanical, Engineering Physics, among others) or related disciplines (such as Applied Mathematics, Physics, and Physical Chemistry) have a unique opportunity to pursue their graduate education within the interdisciplinary Engineering PhD Program at TTU where Chemical Engineering is a strong partner. Graduates of the program have received prestigious NSF and NIH postdoctoral fellowships and leading research positions in premier national and international companies. With high emphasis on doctoral level work, an award winning faculty working with a collegial collaborative approach (with colleagues from the College of Engineering, College of Business, and College of Art and Sciences) offers cutting-edge research projects in Advanced Materials (Nanocomposite Hydrogels, Ceramics and Cement, Polymeric Membranes, etc.), Electrical-based Systems (Electrocatalysis, Electrokinetics, Electrophoresis, Fuel Cells, etc.), and Biological-based Systems (Molecular-based Biomedicine, Clinical Diagnostics, and Micro-Bioseparations). Opportunities in Molecular and Applied and Computational Mathematics are also available. Additionally, students interested in enhancing their expertise in Engineering Education will have exciting avenues in developing methodologies supporting the National Academy of Engineering’s Vision for the Engineer of 2020 Model.

Faculty and students regularly present their research at premiere annual meetings including those supported by AIChE, ACS, AICrS, ASME, AES, and others where students often receive awards for their outstanding contributions. Students and faculty work closely within and across research thrust areas on campus and at national labs and other leading organizations at the national and international level. Competitive graduate assistantships and fellowships are available.

FOR MORE INFORMATION, contact:
TTU Chemical Engineering Department • P.O. Box 5013 • Cookeville, TN 38505-0001 • che@tntech.edu • Phone (931) 372-3297
Fax (931) 372-6352 • Also, visit us on the World Wide Web at: http://www.tntech.edu/che

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OPPORTUNITY

Chemical engineering graduate studies at The University of Texas at Austin are exciting, broad-based and interdisciplinary. The program excels in scholarship, research and education. Fellowships and research assistantships, including generous stipends, tuition and fees, and medical insurance, are provided to qualified Ph.D. applicants.

QUALITY FACULTY

Department faculty awards include ten members of the National Academy of Engineering, two Institute of Medicine members, one National Academy of Science member, and two National Medal of Technology and Innovation Laureates.

RESEARCH AREAS

Approximately $20 million in annual research funding supports programs in: advanced materials, polymers and nanotechnology; biotechnology; energy; environmental engineering; modeling and simulation; and process engineering. Faculty research programs have generated six successful start-up companies.

TOP STUDENTS

The median grade point average of the incoming 2014 graduate class was 3.9 on a 4.0 scale. The department boasts 16 National Science Foundation (NSF) Graduate Fellowships, three National Defense Science and Engineering Graduate Fellows, one Hertz Fellow, one NASA Fellow and four Industrial Fellows (Merck, Aramco, Takenaka, Phillips 66).

PROGRAM RANKINGS & FACTS

<table>
<thead>
<tr>
<th>Faculty</th>
<th>Students</th>
</tr>
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<tbody>
<tr>
<td>— 30 Ph.D. supervising faculty</td>
<td>— 181 graduate students</td>
</tr>
<tr>
<td>— average of 225 peer-reviewed papers a year</td>
<td>— 37% international students</td>
</tr>
<tr>
<td>— won 20% of AIChE major institute awards in recent years</td>
<td>— 31 Ph.D. degrees conferred in 2013</td>
</tr>
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FACILITIES

Students utilize state-of-the-art equipment to conduct research at world-class campus facilities, including the Kuhn Polymer Processing Lab, the Texas Advanced Computing Center, the Texas Materials Institute, the Center for Nano- and Molecular Science and Technology, the Institute for Cellular and Molecular Biology, and the Larry R. Faulkner Nano Science and Technology Building. Students also have access to the Center for Energy and Environmental Research and the Microelectronics Research Center at the J. J. Pickle Research Campus and the new nanoscience building spanning 82,463 square feet.

CONTACT US

Graduate Advisor
200 E. Dean Keeton, Stop C0400
Austin, Texas 78712
Phone: (512) 471-6991
Fax: (512) 475-7824
Email: chemgrad@che.utexas.edu

www.che.utexas.edu
Artie McFerrin Department of CHEMICAL ENGINEERING

RESEARCH AREAS:
Biomedical and Biomolecular Biotechnology
Biofuels
Complex Fluids
Environmental Materials
Microelectronics
Microfluidics
Nanotechnology
Process Safety
Process Systems Engineering
Reaction Engineering
Thermodynamics

GRADUATE PROGRAM:
144 students (Fall 2013)
Strong Ph.D. program
Top 10 in research funding
Financial aid for all doctoral students
Up to $30,000/yr plus tuition, fees and medical insurance benefits

FOR MORE INFORMATION:
Graduate Admissions Office
Artie McFerrin Department of Chemical Engineering
Dwight Look College of Engineering
Texas A&M University || College Station, TX 77843-3122
Phone: (979) 845-3361 || Web Site: wwwche.tamu.edu

FACULTY
M. Akbulut | Ph.D., Univ. of California, Santa Barbara, 2007, Assistant Professor
Nanotechnology, thermal interface materials, enhanced oil recovery
P. Balbuena | Ph.D., University of Texas, Austin, 1996, Professor, GPA Professor
Atomic simulations, predictions of thermodynamic & transport properties
D. Bukur | Ph.D., University of Minnesota, 1974, Professor, Joe M. Neshbitt Professor
Chemical reaction engineering, applied catalysis, mathematical modeling
Z. Cheng | Ph.D., Princeton University, 1999, Associate Professor
Nanotechnology, active soft matter, complex fluids
M. El-Halwagi | Ph.D., Univ. of Calif., Los Angeles, 1990, Professor, McFerrin Professor
Process design, sustainability, eco-industrial systems, hydrocarbon processing
Y. Elabd | Ph.D., Johns Hopkins University, 2001, Professor
Electrochemical energy, ion-conducting polymer membranes
C. Floudas | Ph.D., Carnegie Mellon University, 1986, Chair Professor
Interface of chemical engineering, applied mathematics, operations research
G. Froment | Ph.D., University of Gent, Belgium, 1957, Research Professor
Kinetic & process modeling of hydrocracking, catalytic cracking, steam reforming
C. Glover | Ph.D., Rice University, 1974, Associate Department Head, Professor
Asphalt materials rheological properties, binder oxidation on pavements
M. Green | Ph.D., Massachusetts Institute of Technology, 2007, Associate Professor
Dispersion, rheology, phase behavior of nanomaterials
K. Hall | Ph.D., Univ. of Oklahoma, 1967, Professor, Jack E. & Frances Brown Chair
Thermodynamic properties of fluids & their mixtures, process & product design
J. Holste | Ph.D., Iowa State University, 1973, Professor
Measurement & correlation of thermodynamic fluid properties at high pressures
M. Holtzapple | Ph.D., University of Pennsylvania, 1981, Professor
Biochemical engineering, food & feed processing, conversion of alcohol fuels
A. Jayaraman | Ph.D., Univ. of Calif., Irvine, 1998, Professor, Ray Nesbitt Professor
Director of Graduate Program || Systems biology, molecular systems biotechnology
H.-K. Jeong | Ph.D., Univ. of Minnesota, 2004, Associate Professor, Graduate-Recruitment & Admissions Coordinator || Membranes, nanomaterials development
K. Kao | Ph.D., University of California, Los Angeles, 2005, Associate Professor
Genomics, systems biology, biotechnology
M. Karim | Ph.D., Univ. of Manchester (UK), 1977, Professor, Michael O’Connor Chair II
Department Head || Advanced process control & optimization, biofuels, biotechnology
C. Kravaris | Ph.D., California Institute of Technology, 1984, Professor
Nonlinear systems, process control
Y. Kuo | Ph.D., Columbia University, 1979, Professor, Dow Professor
Nano & microelectronics, semiconductors, thin films
J. Lutkenhaus | Ph.D., Massachusetts Institute of Techn., 2007, Assistant Professor
Organic thin films, nanomaterials
M. Mannan | Ph.D., Univ. of Oklahoma, 1986, Professor, Michael O’Connor Chair I
Director, Mary Kay O’Connor Process Safety Center || Process safety, aerosol research
C. Mashuga | Ph.D., Michigan Technological Univ., 1999, Assistant Professor
Flammability, evaluation of fire & explosion hazards
S. Pistikopoulos | Ph.D., Carnegie Mellon University, 1988, Chair Professor
Process synthesis & the environment, operability in process design & optimization
J. Seminario | Ph.D., Southern Ill. Univ., 1988, Professor, Lanzaert & Herbert Fox Professor
Nanotechnology, molecular simulation, computational chemistry
V. Ugaz | Ph.D., Northwestern University, 1999, Professor, K. R. Hall Professor
Director of Undergraduate Program || Microfabricated bioseparation systems
S. Vaddiraju | Ph.D., University of Louisville, 2006, Assistant Professor
Polymer, vapor phase techniques, nanomaterials, in-situ & ex-situ schemes
B. Willhite | Ph.D., University of Notre Dame, 2003, Associate Professor
Reaction engineering, chemical kinetics, transport processes, multi-layer catalytics
J. H. Wu | Ph.D., Texas A&M University, 2006, Assistant Professor
Biosensors, nanotechnology, infectious disease screening, novel materials

Chemical Engineering Education
Chau-Chyun Chen
Massachusetts Institute of Technology
Molecular thermodynamics, phase equilibria, process modeling and simulation

Harvinder Singh Gill
Georgia Institute of Technology
Drug and vaccine delivery, bionanomaterials, immunomodulation

Ronald C. Hedden
Cornell University
Networks, gels, and elastomers, biofuels, polymer processing

Sheima Jatib-Khatib
University of Madrid
Heterogeneous catalysis, Operando Spectroscopy, membrane reactors

Rajesh Khare
University of Delaware
Molecular dynamics and simulations of polymers and soft matter

Carla Lacerda
Colorado State University
Mitrval heart valve degeneration: models, mechanisms, and prevention

Wei Li
University of Toronto
Cell/polymer interactions, cell microenvironments, biomedical devices

Jeremy Marston
University of Birmingham
Experimental fluid dynamics, granular media, high-speed imaging

Gregory B. McKenna
University of Utah
Polymer and soft matter physics, rheology, nanorheology, nanomechanics

Nurxat Nuraje
City University of New York
Enhanced oil recovery, photocatalysis, renewable energy

Al Sacco, Jr. (Dean)
Massachusetts Institute of Technology
Transition metal and acid catalysts, zeolite synthesis

Sindee L. Simon (Chair)
Princeton University
Physics of glasses, nanoconfined reactions, calorimetry, dilatometry

Siva A. Vanapalli (Graduate Advisor)
University of Michigan
Microfluidics, mechanics of cells and biopolymers, colloidal assembly

Mark W. Vaughn (Undergrad. Advisor)
Texas A & M University
Nitric oxide in microcirculation, membrane transport

Brandon L. Weeks (Associate Chair)
Cambridge University
High explosives, nanolithography, microcantilever, crystal growth

Theodore F. Wiesner
Georgia Institute of Technology
Solar energy, hydrogen production, CO₂ mitigation
The Department of Chemical & Environmental Engineering at The University of Toledo offers graduate programs leading to M.S. and Ph.D. degrees. We are located in state of the art facilities in Nitschke Hall and our dynamic faculty offer a variety of research opportunities in contemporary areas of chemical engineering.

SEND INQUIRIES TO:
Graduate Studies Advisor
Chemical & Environmental Engineering
The University of Toledo
College of Engineering
2801 W. Bancroft Street
Toledo, Ohio 43606-3390
419.530.8080 • www.che.utoledo.edu
cheedpt@eng.utoledo.edu
The University of Toronto ranks highest in Canada in Chemical Engineering. (2014 QS World Ranking)

From the environment and human health to climate change and sustainable energy, the world is facing tremendous challenges. We have one of the strongest research and teaching faculties in North America with an outstanding international reputation for innovative research addressing these urgent issues in the bioprocessing, financial, health, water treatment, resource extraction, and pulp and paper sectors. Our unique blend of engineering and applied chemical and biochemical sciences will give you a powerful combination of skills. You will do high-impact work on real-world problems in our exceptional facilities, right in the heart of one of the most vibrant and multi-cultural cities in the world. Our department is part of Canada’s largest university and offers superb infrastructure, strong industrial connections, many opportunities for professional development beyond the lab, international exchanges, a collegial atmosphere, and guaranteed student funding for MASc and PhD students.

33 faculty members (2014)
219 graduate students (2013)
$21M total research funding (2013)
19 spin-off companies since 1970

RESEARCH AREAS:
Biomolecular & biomedical engineering
Bioprocess engineering
Chemical & material process engineering
Environmental science & engineering
Informatics
Pulp & paper
Surface & interface engineering
Sustainable energy

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For more information:
Graduate Coordinator, Dept. of Chemical Engineering & Applied Chemistry
University of Toronto, 200 College St., Room 212, Toronto, ON, M5S 3E5
416.946.3987 | gradassist.chemeng@utoronto.ca
Department of Chemical 
and Biological Engineering

Research Areas:

- Batch Process Modeling, Optimization, Systems Engineering
- Biomaterials, Tissue Engineering
- Biomolecular Engineering, Cell Engineering
- Bionanotechnology, Biosensors, Smart Biopolymers
- Heterogeneous Catalysis, Nanocatalysis, Reaction Kinetics
- Mass Transfer with Chemical Reaction, Separation Process Modeling
- Metabolic Engineering, Systems Biology

The department offers M. Eng., M. Sci., and Ph.D. degrees in Chemical Engineering and a Ph.D. degree in Biotechnology Engineering. The curriculum emphasizes both rigor and breadth through core and elective coursework in addition to thesis research. In partnership with the School of Engineering, the department also offers M. Eng. and M. Sci. degrees in Bioengineering. The departmental track in Cell and Bioprocess Engineering focuses on bioprocess design and optimization with an emphasis on molecular and cellular processes.

Department Faculty

Linda Abriola, Dean of School of Engineering Ph.D., Princeton University
Kyongbum Lee, Department Chair Ph.D., M.I.T.
Ayse Asatekin Ph.D., M.I.T.
Gregory D. Botsaris, Emeritus Ph.D., M.I.T.
Maria Flytzani-Stephanopoulos Ph.D., University of Minnesota
Christos Georgakis Ph.D., University of Minnesota
David L. Kaplan Ph.D., Syracuse University
Steven Matson Ph.D., University of Pennsylvania
Jerry H. Meldon Ph.D., M.I.T.
Derek Mess Ph.D., M.I.T.
Nikhil U. Nair, Ph.D., University of Illinois
Matthew Panzer Ph.D., University of Minnesota
Daniel R. Ryder Ph.D., Worcester Polytechnic Institute
Nak-Ho Sung, Emeritus Ph.D., M.I.T.
Emmanuel S. Tzanakakis Ph.D., University of Minnesota
Ken Van Wormer, Emeritus Ph.D., M.I.T.
Hyunmin Yi Ph.D., University of Maryland

Visit our website!
http://engineering.tufts.edu/chbe

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Science & Technology Center
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E-mail: chbe@tufts.edu
Application materials and information about the graduate studies at Tufts University are available on the web at http://gradstudy.tufts.edu/.
OUR FACULTY AND RESEARCH

Julie N. L. Albert | Assistant Professor
Nanostructured Polymeric Materials, Stimuli-responsive Materials, Thin Film Morphologies, Surface Science, Combinatorial Methods, Solar Energy, Cancer Metastasis

Hank Ashbaugh | Associate Professor
Classical Thermodynamics and statistical Mechanics, Molecular Simulation, Multi-Scale Modeling of Self-Assembly and Nanostructured Materials

W T. Godbey | Associate Professor
Gene Delivery, Cellular Engineering, Molecular Aspects of Nonviral Transfection, Biomaterials

Vijay John | Professor
Self-assembly and Nanostructured materials, Polymer/Nanocomposites, Biomolecular Materials, Microemulsions

Brian S. Mitchell | Professor
Nanostructured Materials, Fiber Technology, Materials Processing, Composites

Kim C. O’Connor | Professor
Stem Cell Technology, mesenchymal cells, clonal heterogeneity, cell signaling, aging, regenerative therapies

Kyriakos D. Papadopoulos | Professor

Noshir S. Pesika | Assistant Professor
Nanomaterial Synthesis and Characterization, Surface functionalization and Rheology, Bio-inspired Materials, Surface Science, Electrochemistry

Lawrence R. Pratt | Professor
Statistical Mechanics and Thermodynamics, Theory of Liquids and Solutions, Molecular Biology, Electrochemical Capacitors and Energy

Anne Skaja Robinson | Professor and Department Chair
Molecular and cellular engineering for improved protein production, developing cellular biosensors for understanding and control of disease

Katie C. Russell | Professor of Practice
Stem cell technology, clonal heterogeneity, flow cytometry, sorting strategies for mesenchymal stem cell enrichment

Daniel F. Shantz | Professor
New materials to address challenges in energy and sustainability

THE TULANE CBE GRADUATE EXPERIENCE

- Tulane's CBE program is one of the oldest Chemical Engineering programs in the United States
- The small faculty (11) and graduate student body (35) leads to a student-first focus
- Multiple interdisciplinary research initiatives across academic programs
- CBE is actively engaged in university initiatives in Health, Energy, and Environment
- Tulane is located in New Orleans, a vibrant and culturally rich city

An environment that fosters an intellectually challenging, personal, and rewarding graduate experience

For Additional Information, Please Contact
Dr. Daniel F. Shantz, Graduate Coordinator
Tel: (504) 862-3170 E-mail: dshantz@tulane.edu
Visit us at http://tulane.edu/sse/cbe
Engineering the World

The University of Tulsa

The University of Tulsa is Oklahoma's oldest and largest independent university. Approximately 4,200 students pursue more than 70 major fields of study and graduate programs in more than 25 disciplines.

Tulsa, Oklahoma

Off-campus activities abound in Tulsa, one of the nation's most livable cities. Our temperate climate, with four distinct seasons, is perfect for year-round outdoor activities. With a metropolitan population of 888,000, the city of Tulsa affords opportunities for students to gain internship and work experience in its dynamic data processing, petroleum, medical, and financial industries. One can also enjoy world-class ballet, symphony and theatre performances, and exhibits in the cultural community. Annual events include Mayfest, Oktoberfest, the Chili Cook-off and Bluegrass Festival, the Tulsa Run, and the Jazz and Blues festivals.

Chemical Engineering at TU

TU enjoys a solid international reputation for expertise in the energy industry, and offers materials, environmental and biochemical programs. The department places particular emphasis on experimental research, and is proud of its strong contact with industry.

The department offers a traditional Ph.D. program and three master's programs:
- Master of Science degree (thesis program)
- Master of Engineering degree (a professional degree that can be completed in 18 months without a thesis)
- Special Master's degree for nonchemical engineering undergraduates

Financial aid is available, including fellowships and research assistantships.

The Faculty

S.A. Cremaschi • Engineering complex systems, optimization under uncertainty
D.W. Crunkleton • Alternative energy, transport phenomena
L.P. Ford • Kinetics of dry etching of metals, surface science
T. W. Johannes • Directed evolution, biocatalysis, biosynthesis, metabolic engineering
F.S. Manning • Industrial pollution control, surface processing of petroleum
C.L. Patton • Thermodynamics, applied mathematics
G.L. Price • Zeolites, heterogeneous catalysis
K.L. Sublette • Bioremediation, biological waste treatment, ecological risk assessment
K.D. Wisecarver • Multiphase reactors, multiphase flows

Further Information
Graduate Program Director • Chemical Engineering Department
The University of Tulsa • 800 South Tucker Drive • Tulsa, Oklahoma 74104-3189
Phone (918) 631-2227 • Fax (918) 631-3268
E-mail: chegradadvisor@utulsa.edu • Graduate School application: 1-800-882-4723

The University of Tulsa has an Equal Opportunity/Affirmative Action Program for students and employees.
The University of Utah's Department of Chemical Engineering provides cutting-edge graduate research opportunities in energy and fuels, biotechnology, environmental engineering, nanotechnology, medicine and pharmacy. Our faculty is tightly integrated with the Institute for Clean and Secure Energy, Nano Institute of Utah, the Energy and Geosciences Institute and the Nuclear Engineering Program. Students have access to state-of-the-art laboratory facilities and a network of faculty with diverse research expertise.

In addition to high-quality research, you will find our faculty is dedicated to teaching. Many professors have earned outstanding teaching awards and routinely rank among the top instructors in the College of Engineering. Graduate students enjoy the collegiality of our department and location of our campus, which provides many recreational opportunities outside the classroom and laboratory.

Our department offers the following degrees:

- PhD in Chemical Engineering*
- MS in Chemical Engineering*
- MS in Petroleum Engineering (distance or on-campus)
- MS/MBA in collaboration with the David Eccles School of Business

*Student financial support for these degrees is available through fellowships and research assistantships

For more information about our graduate programs please visit our website at che.utah.edu/graduate

STUDENT SUCCESS

Our former graduate students are now employed at top-tier, nationally recognized corporations, academic institutions and laboratories such as:

- Intel
- John Zink Company LLC
- National Renewable Energy Laboratory
- Conoco Phillips
- GE Energy
- Afton Chemical
- USG Corporation
- Devon Energy
- CD Adapco
- Halliburton
- Massachusetts Institute of Technology
- Brigham Young University

RECREATION

Utah is home to five national parks and is legendary for outdoor recreation activities. The Wasatch mountains offer excellent hiking and mountain biking and include 10 world-class ski resorts within 30 minutes of Salt Lake City.

FACULTY:

Anthony Butterfield
Milind Deo (Chair)
Eric Eddings
Andrew Fry
Michael Hoepfner
Tatjana Jevremovic
JoAnn Lighty
Jules Magda
John McLennan
Manoranjan Misra
Sowmitra Mohanty
Agniesz Ostafin
Leonard Pease
Marc Porter
Terry Ring
Richard Roehner
Geoffrey Silcox
Stuart Simmons
Mikhail S Kilari
Philip Smith
Sean Smith
Jennifer Spindel
James Sutherland
Jeremy Thornock
Edward Trujillo
Jost Wendt
Kevin Whitty
Graduate Study Leading to the Ph.D. and M.S. Degrees

Graduate work in chemical engineering provides an opportunity for study and research at the cutting edge - to contribute to shaping a new model of what chemical engineering is and what chemical engineers do. At Vanderbilt University we offer a broad range of research projects in chemical and biomolecular engineering, with wide ranging opportunities for interdisciplinary work and professional development. Focus areas include:

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- Biomaterials and tissue engineering
- Computational molecular engineering and nanoscience
- Metabolic engineering
- Microelectronic and ultra-high temperature materials
- Nanoparticles for drug and gene delivery
- Surface modification and molecular self-assembly

Research assistantships offer a competitive stipend, full tuition waiver, and health insurance. Additionally School and University fellowship awards are available to outstanding applicants. To find out more visit:

http://engineering.vanderbilt.edu/chbe/

Vanderbilt, ranked in the top 20 nationally for its leadership in both research and teaching, is located on 330 park-like acres just one and one-half miles from downtown Nashville, one of the most vibrant and cosmopolitan mid-sized cities in the United States. Ten schools offer both an outstanding undergraduate and a full range of graduate and professional programs. With a prestigious faculty of more than 2,800 full-time and 300 part-time members, Vanderbilt attracts a diverse student body of approximately 6,500 undergraduates and 5,300 graduate and professional students from all 50 states and over 90 foreign countries.

Rizia Bardhan (Ph.D., Rice University)
Engineering hybrid nanoscale materials; plasmonic and nanophotonics; solar energy conversion; electrochemical energy storage; nanomedicine; nanobiosensing and biomimetics

Peter T. Cummings (Ph.D., University of Melbourne)
Computational nanoscience and nanotechnology; molecular modeling of fluid and amorphous systems; parallel computing; cell-based models of cancer tumor growth

Kenneth A. Debelak (Ph.D., University of Kentucky)
Catalytic reactions for renewable fuels; oscillators in bioelectronic devices; development of plant-wide control algorithms; intelligent process control

Scott A. Guelcher (Ph.D., Carnegie Mellon University)
Biomaterials; bone tissue engineering; polymer synthesis and characterization; drug and gene delivery

G. Kane Jennings (Ph.D., Massachusetts Institute of Technology)
Molecular and surface engineering; polymer thin films; solar energy conversion; tribology; fuel cells

Paul E. Laibinis (Ph.D., Harvard University)
Self-assembly; surface engineering; interfaces; chemical sensor design; biosurfaces; nanotechnology

Matthew J. Lang (Ph.D., University of Chicago)
Molecular and cellular biophysics; functional measurement of biological motors and cell machinery; instrumentation: optical tweezers, microscopy and single molecule fluorescence

M. Douglas LeVan (Ph.D., University of California, Berkeley)
Novel adsorbent materials; adsorption equilibria; mass transfer in nanoporous materials; adsorption and membrane processes

Clare McCabe (Ph.D., University of Sheffield)
Molecular modeling of complex fluids and materials; biological self-assembly; molecular rheology and tribology

Peter N. Pintauro (Ph.D., University of California, Los Angeles)
Electrochemical engineering; fuel cell membranes; ion uptake and transport models for ion-exchange membranes; organic electrochemical synthesis

Bridget R. Rogers (Ph.D., Arizona State University)
Surfaces, interfaces, and films of microelectronic and ultra-high temperature materials; determination of process/property/performance relationships

John T. Wilson (Ph.D., Georgia Institute of Technology)
Biomaterials, drug delivery, regenerative medicine, polymer chemistry, colloids and surface engineering, nanotechnology, vaccines, cancer immunotherapy, diabetes, cell transplantation

Jamey D. Young (Ph.D., Purdue University)
Metabolic engineering; systems biology; diabetes, obesity and metabolic disorders; tumor metabolism; autotrophic metabolism

For more information:
Director of Graduate Studies
Department of Chemical & Biomolecular Engineering
Vanderbilt University • VU Station B 351604
Nashville, TN 37235-1604
Email: chegrad@vanderbilt.edu

Chemical Engineering Education
Graduate Studies in Chemical Engineering

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Charlottesville, VA 22904-4741
434.924.7778

E-mail: cheadmis@virginia.edu
Website: www.che.virginia.edu

Giorgio Carta, PhD, University of Delaware
Bioseparations, protein chromatography, transport phenomena in adsorption and ion exchange

Joshua J. Choi, PhD, Cornell University
Nanomaterials for solar energy conversion, nanoparticle self-assembly, materials chemistry, optoelectronic devices

Robert J. Davis, PhD, Stanford University
Heterogeneous catalysis, reaction kinetics, conversion of renewable resources

Roseanne M. Ford, PhD, University of Pennsylvania
Mass transfer and chemical reaction in biological and environmental systems

Geoffrey M. Geise, PhD, The University of Texas at Austin
Macromolecular engineering for separations and clean energy, water purification, membrane design, ion and water transport, polymer science

David L. Green, PhD, University of Maryland, College Park
Nanoparticle engineering, complex fluids, colloid and interface science, soft materials

Gary M. Koenig, Jr., PhD, University of Wisconsin-Madison
Materials for energy storage, electrochemistry, colloid and interface science, nanomaterials, soft materials

Kyle Lampe, PhD, University of Colorado
Neural tissue engineering, biomaterials, drug delivery, redox regulation of stem cell fate, engineering cell-interactive microenvironments

Michael R. Shirts, PhD, Stanford University
Molecular modeling, thermodynamics and statistical mechanics of complex fluids, pharmaceutical design, nanomolecular self-assembly
Chemical Engineering at Virginia Tech

Faculty...

Modeling of chemical and biological systems

Donald G. Baird (Wisconsin)
Polymer processing, non-Newtonian fluid mechanics

David F. Cox (Florida)
Catalysis, ultrahigh vacuum surface science

Richey M. Davis (Princeton)
Colloids and polymer chemistry, nanostructured materials

William A. Ducker (Australian Natl. Univ.)
Colloidal forces, surfactant self-assembly, atomic force microscopy

Aaron S. Goldstein (Carnegie Mellon)
Tissue engineering, interfacial phenomena in bioengineering

Ayman M. Karim (New Mexico)
Heterogeneous catalysis, nucleation/growth of colloidal nanoparticles, microreactors for in-situ/operando characterization

Erdogan Kiran (Princeton)
Supercritical fluids, polymer science, high pressure techniques

Y.A. Liu (Princeton)
Pollution prevention and computer-aided design

Chang Lu (Illinois)
Microfluidics for single cell analysis, gene delivery

Eva Marand (Massachusetts)
Transport through polymer membranes, advanced materials for separations

Stephen M. Martin (Minnesota)
Soft materials, self-assembly, interfaces

Padma Rajagopalan (Brown)
Polymeric biomaterials, cell and tissue engineering

Abby R. Whittington (Illinois)
Tissue engineering, controlled release of proteins

Hongliang Xin (Michigan)
Computational catalysis, kinetic theory of electron transfer processes, understanding-driven catalyst screening

Virginia Tech
For further information write or call the director of graduate studies or visit our webpage.
Department of Chemical Engineering
245 SEB, 635 Prices Fork Rd., Virginia Tech, Blacksburg VA 24061
Telephone: 540-231-5771  •  Fax: 540-231-5022
e-mail: dianec@vt.edu  •  http://www.che.vt.edu
The University of Washington ranks among the world's top research universities and is the #1 public university in federal funding. Chemical Engineering graduate students have opportunities to do research at flagship interdisciplinary centers including the Molecular Engineering and Sciences Institute (http://www.moles.washington.edu/) and the Clean Energy Institute (http://www.cei.washington.edu/).

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- DeForest | Jiang | Ratner
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- Sensing
- Organic electronics
- Jenekhe | Jiang | Yu
- Photovoltaics
- Energy polymers
- Electrochemical conversion
- Energy storage
- Energy systems management
- Fuel cells
- Adler | Hillhouse | Holmberg
- Jenekhe | Pozzo | Subramanian
- Schwartz | Stueve | Yu
- Baneyx | Beck | Carothers
- Lidstrom | Pfleiderer
- Metabolic engineering
- Synthetic biology
- Systems biology
- Biomolecular engineering
- Biocompatible materials
- Antifouling materials
- Bio-inspired materials
- Electronics
- Surfaces and interfaces
- Nanomedicine
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www.voiland.wsu.edu
Graduate Study in the Department of Energy, Environmental and Chemical Engineering

Washington University in St. Louis

Masters and Ph.D. Programs

Dept. of Energy, Environmental & Chemical Engineering

The department has a focus on environmental engineering science, energy systems, and chemical engineering. The department provides integrated and multidisciplinary programs of scientific education. Our mission is accomplished by:

- Instilling a tradition of "life-long learning"
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- Access to state-of-the-art facilities and instrumentation

The basic degree is an undergraduate degree in chemical engineering. Graduate degrees (Master of Science and Doctor of Philosophy) are offered in Energy, Environmental and Chemical Engineering on completion of a course of study and research work. Professional Masters degrees with tracks in Energy and Environmental Management, International Development are also offered. A minor is offered to undergraduate students interested in environmental engineering and can be selected by any engineering or science student. The program is also affiliated with the Environmental Studies Program.

R. Axelbaum - Nanoparticle Synthesis, Combustion Engineering
P. Biswas - Aerosol Science & Technology, Environmental & Energy Nanotechnology
R. Chakrabarty - Aerosol Science & Technology, Aerosol Optics, Climate Issues
M. Dudukovic - Multiphase Reaction Engineering, Tracer Methods, Environmental Engineering
J. Fortner - Aquatics, Environmental Chemistry of Nanomaterials
M. Foston - Biomass Resources, Renewable Synthetic Polymers
D. Giammar - Aquatic Chemistry, Water Quality Engineering, Fate & Transport of Inorganic Contaminants
J. Gleaves - Heterogeneous Catalysis, Surface Science, Microstructured Materials
Y.S. Jun - Aquatic Processes, Molecular Issues in Chemical Kinetics
C. Lo - Aquatic Processes, Biomineral Structure & Reactivity at Environmental Interfaces
T. Moon - Metabolic Engineering, Bioremediation
H. Pakrasi - Systems Biology
P. Ramachandran - Chemical Reaction Engineering, Boundary Element Methods
V. Subramanian - Multiscale Phenomena, Electrochemical Systems and Applied Mathematics
Y. Tang - Metabolomics, Systems Biology
E. Thimsen - Nanomaterial Synthesis, Aerosol Reactors
J. Turner - Environmental Reaction Engineering, Air Quality Policy & Analysis, Aerosol Science & Technology
B. Williams - Aerosols, Global Climate Issues, Atmospheric Sciences
F. Zhang - Metabolic Engineering, Protein Engineering, Synthetic & Chemical Biology

Graduate Admissions Committee, Washington University in St. Louis, Department of Energy, Environmental and Chemical Engineering
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For additional information on financial support and admission requirements:

Judy Caron
Graduate Co-ordinator
Chemical Engineering
519-888-4567, ext. 32620
j2.caron@uwaterloo.ca
CHEMICAL ENGINEERING
MS and PhD Programs

FACULTY
Sushant Agarwal
West Virginia University
Brian J. Anderson
Massachusetts Institute of Technology
Debangsu Bhattacharyya
Clarkson University
Eugene V. Cilento
Dean
University of Cincinnati
Dady B. Dadyburjor
University of Delaware
Cerasela Z. Dinu
Max Planck Institute of Molecular Cell Biology and Genetics and Dresden University
Pradeep P. Fulay
Associate Dean
University of Arizona
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Chair
University of Delaware
Robin S. Hissam
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Northwestern University
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Institute of Chemistry, CAS
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Tufts University
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Hanjing Tian
Lehigh University
Richard Turton
Oregon State University
Yong Yang
Ohio State University
John W. Zondlo
Carnegie Mellon University

RESEARCH AREAS INCLUDE:
Bioengineering, Systems Biology
Biomaterials, Tissue Engineering
Bionanotechnology, Biomimetics
Catalysis and Reaction Engineering
Coal/Biomass Gasification
Coal/Biomass Liquefaction
Electronic Materials, Nanostructures
Energy Systems Modeling
Fluid-Particle Sciences
Fuel Cells
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Nanocomposites, Nanoparticles
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West Virginia University
BENJAMIN M. STATLER COLLEGE OF ENGINEERING AND MINERAL RESOURCES

For Application Information:
Professor Dady B. Dadyburjor
Graduate Admissions Committee
Department of Chemical Engineering
PO Box 6102
West Virginia University
Morgantown, WV 26505-6102
304-293-2111
che-info@mail.wvu.edu

www.che.statler.wvu.edu
The University of Wisconsin-Madison Department of Chemical and Biological Engineering has a tradition of excellence dating to 1905, consistently ranking among the top programs in the U.S.

Award-winning faculty, outstanding students and a collegial atmosphere create an intellectually stimulating environment.

We offer cutting-edge research opportunities in biotechnology, nanotechnology, complex fluids, molecular and multiscale modeling, environmental engineering, atomic-scale design of surface reactivity, heterogeneous catalysis, and process systems engineering.

Research in the department is highly interdisciplinary, capitalizing on programs of national prominence such as the NSF Materials Research Science and Engineering Center (MRSEC), the NSF Nanoscale Science and Engineering Center (NSEC), the Great Lakes Bioenergy Research Center (GLBRC), a leading medical school, and many NIH-funded graduate training programs, as well as graduate internships and international collaborations.

The UW campus has uniformly strong programs in all areas of the biological, chemical, and physical sciences.

The city of Madison is consistently ranked as a top community in which to live, work, and play.

### Faculty research areas

- **Nicholas L. ABBOTT**
  - Interfacial phenomena, colloid science, soft materials, nanotechnology, biomolecular interfaces

- **James A. DUMESIC**
  - Kinetics and catalysis, surface chemistry, energy from renewable resources

- **Michael D. GRAHAM**
  - Fluid mechanics, complex fluids, microfluidics, applied and computational mathematics

- **George W. HUBER**
  - Biomass conversion, heterogeneous catalysis and kinetics, high-throughput testing, catalyst characterization

- **Daniel J. KLINGENBERG**
  - Colloid science, complex fluids, suspension rheology

- **Thomas F. KUECH** (Chair)
  - Semiconductor and advanced materials processing, solid-state, electronic, and nanostructured materials, interface science, solar energy

- **David M. LYNN**
  - Soft Materials, Nanotechnology, Polymers, Biotechnology, Drug Delivery

- **Christos T. MARAVELIAS**
  - Production planning and scheduling, supply chain management, process synthesis, novel material discovery

- **Manos MAVRIKAKIS**
  - Thermodynamics, kinetics and catalysis, surface science, computational chemistry, electronic materials, fuel cells, hydrogen economy

- **Regina M. MURPHY**
  - Biomedical engineering, protein-protein interactions, neurodegenerative disorders

- **Sean P. PALECEK**
  - Stem cell engineering, cell adhesion, cell signaling

- **Brian F. PFLEGER**
  - Synthetic biology, biotechnology, protein engineering, sustainable chemical production

- **James B. RAWLINGS**
  - Process modeling, dynamics and control, chemical reaction engineering, statistical and computational methods in systems biology

- **Jennifer L. REED**
  - Systems biology, metabolic model development and analysis, metabolic engineering

- **Thatcher W. ROOT**
  - Green chemistry, renewable resources, catalysis, spectroscopy

- **Eric V. SHUSTA**
  - Drug delivery, protein engineering, biopharmaceutical design

- **Ross E. SWANEY**
  - Process design, synthesis, modeling, and optimization

- **John YIN**
  - Systems biology, virus-cell interactions, immunology, microfluidics

For more information, please contact:

Graduate Program Office
Dept. of Chemical & Biological Engineering
University of Wisconsin–Madison
1415 Engineering Drive
Madison, WI 53706-1607

gradoffice@che.wisc.edu
Phone: 608/263-3138

www.che.wisc.edu

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**Chemical Engineering Education**
RESEARCH AREAS & FACULTY

Bacterial Adhesion · Biomaterials · Nanobiotechnology
Terri A. Camesano, PhD, Pennsylvania State University

Separation Processes · Engineering Education
William M. Clark, PhD, Rice University

Catalysis and Reaction Engineering · Fuel Cells and Hydrogen
Ravindra Datta, PhD, University of California, Santa Barbara

Computational Chemistry · Catalysis · Metal Oxide Materials
N. Aaron Deskins, PhD, Purdue University

Engineering Education · Teaching and Learning · Assessment
David DiBiasio, PhD, Purdue University

Transport in Chemical Reactors · CFD · Microreactors
Anthony G. Dixon, PhD, University of Edinburgh

Chemical Process Safety · Environmental and Energy Systems
Nikolaos K. Kazantzis, PhD, University of Michigan

Chemical Process Safety · Air Pollution Control · Pollution Prevention
Stephen J. Kmiotek, PhD, Worcester Polytechnic Institute

Inorganic Membranes · Hydrogen Separation and Membrane Reactors
Yi Hua Ma, ScD, Massachusetts Institute of Technology

Biomaterials · Polymer Films and Interfaces
Amy M. Peterson, PhD, Drexel University

Kinetics and Reactor Analysis · Particulate Synthesis · Water Purification
Robert W. Thompson, PhD, Iowa State University

Renewable Energy · Liquid and Biomass Fuels · Reaction Engineering
Michael T. Timko, PhD, Massachusetts Institute of Technology

Bionanotechnology · Bioseparations · BioMEMS Microfluidics
Susan Zhou, PhD, University of California, Irvine

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Worcester Polytechnic Institute
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chemeng@wpi.edu

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The Department of Chemical and Petroleum Engineering at the University of Wyoming (UW) offers cutting edge research opportunities to develop new technologies in chemical processing and refining, biological and biomedical science, and alternative and conventional energy sources. The department is the beneficiary of strong and continuous support from the University, the School of Energy Resources, and the State of Wyoming.

Engineering Science
- Applied molecular and macromolecular thermodynamics
- Green manufacturing processes
- Process design
- Microfluidics
- Environmental engineering
- Macromolecular phase equilibria

Material Science
- Nanomaterials
- Heterogeneous catalysis
- Biomaterials
- Membranes
- Soft matter

Energy Research
- Transport in porous media
- Enhanced oil recovery
- Interfacial phenomena
- Fossil derived synfuels
- Geomechanics
- Reservoir engineering
- Bioenergy

Biological Science
- Tissue engineering
- Biomedical engineering
- Biointerfaces
- Biosensors
- Regenerative Medicine

Faculty
- Hertanto Adidharma, Louisiana State University
- Vladimir Alvarado, University of Minnesota
- Saman Aryana, Stanford University
- David Bagley, Cornell University
- David Bell, Colorado State University
- Maohong Fan, Osaka University; Iowa State University
- Lamia Goual, Imperial College London
- Joseph Holles, University of Virginia
- Patrick Johnson, Columbia University
- Dongmei (Katie) Li, University of Colorado
- Norman Morrow, University of Leeds
- John Oakey, Colorado School of Mines
- Luis Felipe Pereira, Stony Brook University
- Mohammad Piri, Imperial College London
- Maciej (Mac) Radosz, Cracow University of Technology
- Mrityunjai Sharma, Washington State University
- Karen Wawrousek, California Institute of Technology
- Shunde Yin, University of Waterloo

*Persons seeking admission to the University of Wyoming shall be considered without regard to race, color, religion, sex, national origin, disability, age, veteran status, sexual orientation, or political belief.
Eric Altman, Ph.D. Pennsylvania

Menachem Elimelech, Ph.D. Johns Hopkins

Drew Gentner, Ph.D. UC Berkeley

Gary Haller, Ph.D. Northwestern

Jaehong Kim, Ph.D. Illinois

Michael Loewenberg, Ph.D. Cal Tech

Chinedum Osuji, Ph.D. M.I.T.

Jordan Peccia, Ph.D. Colorado

Lisa Pfefferle, Ph.D. Pennsylvania

Desirée Plata, Ph.D. M.I.T.

Daniel Rosner, Ph.D. Princeton

André Taylor, Ph.D. Michigan

Paul Van Tassel, Ph.D. Minnesota

Kyle Vanderlick, Ph.D. Minnesota

Corey Wilson, Ph.D. Rice

Julie Zimmerman, Ph.D. Michigan

Joint Appointments

• Michelle Bell (School of Forestry & Environmental Studies)

• Gaboury Benoit (School of Forestry & Environmental Studies)

• Eric Dufresne (Mechanical Engineering & Materials Science)

• Tarek Fahmy (Biomedical Engineering)

• Thomas Graedel (School of Forestry & Environmental Studies)

• Edward Kaplan (School of Management)

• Mark Saltzman (Biomedical Engineering)

• Udo Schwarz (Mechanical Engineering & Materials Science)

• Kurt Zilm (Chemistry)
Faculty and Research Interests

Morris D. Argyle (Berkeley) • heterogeneous catalysis
Larry L. Baxter (BYU) • combustion of fossil and renewable fuels
Bradley C. Bundy (Stanford) • protein production and engineering
Alonzo D. Cook (MIT) • tissue and biomedical engineering
Thomas H. Fletcher (BYU) • pyrolysis and combustion
John H. Harb (Illinois) • coal combustion, electrochemical engineering
William C. Hecker (UC Berkeley) • kinetics and catalysis
John Hedengren (UT Austin) • modeling and optimization for energy systems
Thomas A. Knotts (University of Wisconsin) • molecular modeling
Randy S. Lewis (MIT) • biochemical and biomedical engineering
David O. Lignell (Utah) • computational reacting flow
Matthew J. Memmott (MIT) • nuclear power & safety, reactor design
William G. Pitt (Wisconsin) • materials science
Thomas A. Wheeler (Berkeley) • molecular electrochemistry
W. Vincent Wilding (Rice) • thermodynamics, environmental engineering

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Master of Science in Chemical Engineering

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For further information, contact:
Professor Brandon Vogel
Department of Chemical Engineering
Bucknell University, Lewisburg, PA 17837
Phone 570-577-1114 E-mail bmvo02@bucknell.edu
www.bucknell.edu/graduatetudies

J. Csernica, Chair (Ph.D., M.I.T.)
Diffusion in polymers, polymer surface modification
M.D. Gross (Ph.D., Pennsylvania) Electrochemistry and fuel cell, catalysis
E.L. Jablonski (Ph.D., Iowa State) Thin films, surface chemistry
W.E. King (Ph.D., Pennsylvania) Photodynamic therapy, hemodialysis
J.E. Maneval (Ph.D., U.C. Davis) NMR methods, membrane and novel separations
M.J. Prince (Ph.D., U.C. Berkeley) Environmental barriers, instructional design
T.M. Raymond (Ph.D., Carnegie Mellon) Atmospheric science, organic aerosols, air pollution
R.C. Snyder (Ph.D., U.C. Santa Barbara) Conceptual design crystallization
W.J. Snyder (Ph.D., Penn State) Polymer degradation, kinetics, drag reduction
M.A.S. Vigeant (Ph.D., Virginia) Bacterial Adhesions to surfaces
B.M. Vogel (Ph.D., Iowa State) Biomaterials, polymer chemistry
K. Wakabayashi (Ph.D., Princeton) Polymer hybrid materials sustainable processing
W.J. Wright (Ph.D., Stanford) Mechanical behavior, bulk metallic glasses, nanoindentation

Chemical Engineering Education
CLARKSON UNIVERSITY

Department of Chemical & Biomolecular Engineering
Graduate Study in Chemical Engineering (M.S. and Ph.D. Degrees)

The department research areas include biosensors and bioelectronics, plasma processing in condensed media; surface science, colloids, structured materials and self assembly; thin film deposition and crystallization, membrane processes, chemical mechanical polishing; photovoltaic devices, materials and fabrication; materials for fuel cells; air pollutant sampling and analysis, particulate transport and deposition; receptor modeling; soft matter, polymers and biomaterials; separation processes; and mass transfer and distillation.

Research collaboration is enhanced through the following University centers:

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- Center for Rehabilitation Engineering, Science and Technology (CREST)
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- Advanced Materials, Fuels, & Energy
- Organic Semiconductors & Biomaterials

Faculty
- Rufina Alame (University of Madrid)
- Raveendran Chella (Univ. of Massachusetts - Amherst)
- Nachiket Deshpande (Florida State University)
- Joel R. Fiedler (University of Massachusetts - Amherst)
- Samuel C. Grace (University of Illinois - Chicago)
- Jingliao Guan (Ohio State University)
- Daniel J. Hallinan (Drexel University)
- Darius S. Hsu (University of Kentucky)
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- Yan Li (Ohio State University)
- Bruce R. Locke (North Carolina State University)
- Blaw Ma (University of Southern California)
- Teng Ma (Ohio State University)
- Anant Paravastu (University of California - Berkeley)
- Subramanian Ramakrishnan (Univ. of Illinois - Urbana)
- Loren B. Schreiber (California Institute of Technology)
- Theo M. Siegrist (ETH - Zurich)
- John C. Telotte (University of Florida)

For more information contact:
Department of Chemical and Biomedical Engineering
FAMU-FSU College of Engineering
2525 Pottsdamer Street, Tallahassee, FL 32310-6046
Phone: 850-410-6149; FAX: 850-410-6150; E-Mail: chemical@eng.fsu.edu; Web: www.eng.fsu.edu/cbe

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The department has a highly active research program covering a wide range of interests.

**Faculty and Research Areas:**

- **Wudneh Admassu**—Transport Phenomena, Gas Separations, Biochemical Engineering with Environmental Applications
- **Eric Aston**—Surface Science, Thermodynamics, Scanning Probe Microscopy
- **Indrajit Charit**—Energy Materials (Nuclear and Fossil), High Temperature Mechanical Behavior of Materials, Nanostructured Materials, Advanced Processing and Joining Techniques
- **Dean Edwards**—Application of Computer Modeling and Material Development to Battery Research
- **James Moberly**—Microbial Fuel Cells, Bioenergy, Bioremediation, Metal/Microbe Interactions, Environmental Biotechnology
- **Batric Pesic**—High and Low Temperature Metal Separation Methods
- **Krishnan Raja**—Nanomaterials for Energy Conversion & Storage, Nuclear Materials, Aqueous and Non-aqueous Electrochemistry, and Environmental Degradation of Materials
- **Mark Roll**—Polymers, Composites, Solid Electrolytes and Thin Film Materials
- **Soumya K. Srivastava**—Microfluidics, Bio-separations, Designing Lab-on-a-Chip System for Medical Diagnostic Applications using Electrokinetics Modeling & Simulations, Educational Research
- **Haiyan Zhao**—Catalysis & Kinetics, Materials Characterization, Renewable Energy & Processing (Idaho Falls)

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<td>Demixing-polymerization, polymer materials</td>
<td>Gerard Canella, PhD, U. California-Berkeley, 1985</td>
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<td>Process control, neural networks, fuzzy logic control</td>
<td>Tomas Co, PhD, Massachusetts-Amherst, 1986</td>
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<td>Chemical process safety</td>
<td>Daniel Crowl, PhD, Illinois, 1975</td>
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<td>Metals bioprocessing, separations</td>
<td>Timothy Eisele, PhD, Michigan Tech, 1992</td>
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<td>Bioseparations, virus removal &amp; purification, and biosensors</td>
<td>Caryn Heldt, PhD, North Carolina State Univ., 2006</td>
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<td>Nanoparticle, particulate, and materials processing</td>
<td>S. Komar Kawatra, Chair, PhD, Queensland, 1974</td>
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<tr>
<td>Polymers, composites</td>
<td>Julie King, PhD, Wyoming, 1995</td>
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<tr>
<td>Medical microdevices, electrokineti cs</td>
<td>Adrienne Mierink, PhD, Notre Dame, 2003</td>
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<tr>
<td>Polymer rheology, flow instabilities, complex fluids</td>
<td>Faith Morrison, PhD, Massachusetts-Amherst, 1988</td>
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<tr>
<td>Reactor design, thermodynamics, materials</td>
<td>Michael Mullins, PhD, Rochester, 1983</td>
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<tr>
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<td>Daniel Crowl, PhD, Illinois, 1975</td>
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<td>Reactor design, thermodynamics, materials</td>
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<td>Bio-based products, bio transport</td>
<td>Ching-Peng, PhD, University of Michigan, 1995</td>
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<td>Environmental thermodynamics</td>
<td>Tony Rogers, PhD, Michigan Tech, 1994</td>
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<td>Materials utilization</td>
<td>John Sandell, PhD, Michigan Tech, 1995</td>
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<tr>
<td>Environmental and biochemical engineering</td>
<td>David Shannon, PhD, U. California-Davis, 1991</td>
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<tr>
<td>Biofuels, modeling, bioinformatics</td>
<td>Wan Zhou, PhD, U. California-Los Angeles, 2006</td>
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**Contact:** Dr. Julie King, jaking@mtu.edu • Department of Chemical Engineering • Michigan Technological University • 1400 Townsend Drive • Houghton, MI 49931-1295 • Phone: 906-487-3132 • www.mtu.edu/chemical

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**University of Missouri**

**DEPARTMENT OF CHEMICAL ENGINEERING**

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<td>Sheila N. Baker, PhD</td>
<td>(SUNY-Buffalo)</td>
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<td>Ionic Liquids * Separations * CO2 Sequestration</td>
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<td>Matthew T. Bernards, PhD</td>
<td>(Washington-Seattle)</td>
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<td>Karl D. Hammond, PhD</td>
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<td>Thomas R. Marrero, PhD</td>
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<td>Sustainability * Conducting Polymers * Fuels Emissions</td>
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<td>Patrick J. Pinhero, PhD</td>
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<td>David G. Retzloff, PhD</td>
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<tr>
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<td>Bret D. Ulery, PhD</td>
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<td>Immunology * Tissue Engineering * Peptide Amphiphiles</td>
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<td>Yangchuan Xing, PhD</td>
<td>(Yale)</td>
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<td>PEM Fuel Cells * Electro/Photo Catalysis * Li Ion Batteries</td>
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- Process Simulation
- Molecular Simulation
- Fluidization

Process Design
Separation Processes
Pollution Prevention
Polymers
Phase Equilibria
Reaction Engineering
Renewable Energy
Nanotechnology

Faculty
- Charles J. Coronella (Univ. of Utah)
- Alan Fuchs, Chair (Tufts University)
- Hongfei Lin (Louisiana State Univ.)
- Vaidyanathan Subramanian (Univ. of Notre Dame)
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- Pharmaceutical Engineering (Meenach)
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R.S. Artigue, D.E., Tulane
Process Control, Micro/Ultrafiltration

H.C.S. Chenette, Ph.D., Clemson
Polymer-functionalized Membranes

D.G. Coronell, Ph.D., MIT
Reactor Engineering, Materials, Computation

M.H. Hariri, Ph.D., Manchester, U.K.
Energy, Environment and Safety

D.B. Henthorn, Ph.D., Purdue
Biomaterials, Diagnostic & Therapeutic Devices

K.H. Henthorn, Ph.D., Purdue
Particle Technology, Microfluidics

S.J. McClellan, Ph.D., Purdue
Colloidal and Interfacial Phenomena, Drug Delivery

A.J. Nolte, Ph.D., MIT
Polymers, Surface Science, Materials

S.G. Sauer, Ph.D., Rice
Thermodynamics

A. Serbezev, Ph.D., Rochester
Adsorption, Process Control

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C.F. Abegg, Ph.D., Iowa State
W.B. Bowden, Ph.D., Purdue
J.A. Caskey, Ph.D., Clemson
N.E. Moore, Ph.D., Purdue

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Faculty and Research Areas

Sookie S. Bang (PhD, University of California, Davis)
Biocatalyst, bio-materials, genomics, microbiology

Kenneth M. Benjamin (PhD, University of Michigan)
Molecular modeling, bioenergy, supercritical/ionic fluids

David J. Dixon (PhD, University of Texas, Austin)
Supercritical fluids, membranes, biomass pretreatment

Patrick C. Gilcrease (PhD, Colorado State University)
Biomass conversion, fermentation, coal-bed biomethane

Lori J. Groven (PhD, SD School of Mines and Technology)
Combustion, energetic materials, nanomaterials

Kevin R. Hadley (PhD, Vanderbilt University)
Molecular modeling, nano-materials, pedagogy

Todd J. Menkhaus (PhD, Iowa State University)
Bioseparations, nanofelts, membranes, biomass processing

Jan A. Puszynski (PhD, Inst. of Chem. Tech., Czech. Rep)
Nanotechnology, combustion synthesis, energetic materials

David R. Salem (PhD, University of Manchester, U.K.)
Polymers, bio/nano composites, p-s-p relationships

Rajesh K. Sani (PhD, Panjam University, India)
Bioremediation, metabolic engineering, biotechnology

Rajesh V. Shende (PhD, University of Mumbai, India)
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Shikha Nangia
Dacheng Ren
Ashok S. Sangani
Pranav Soman
Radhakrishna Sureshkumar
Lawrence L. Tavlarides
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Reservoir Engineering and Production

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Ph.D., Texas A&M University
Thermodynamics, Physical Property Measurements, Process Simulation

P. L. MILLS
D.Sc., Washington University in St. Louis
Kinetics, Catalysis, and Reaction Engineering

C. D. MURPHY
Ph.D., Carnegie Mellon, P.E.

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