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PEDAGOGY AND SOME FACTORS THAT INFLUENCE HOW WE FACILITATE STUDENT LEARNING

DONALD R. WOODS
McMaster University • Hamilton Ontario Canada

How might we facilitate student learning? In the 1960s when I joined academia, I thought I taught students via lectures with 50 minutes of teach talk. Yes, I tried to make the lectures interesting, entertaining, and motivating. Then I joined ASEE and began to realize that many new approaches were being developed to improve student learning. In this paper I’ll note the publications and major events that influenced me in my journey to improve student learning.

Then I’ll shift gears and give an overview of idealized career paths of persons who took different approaches to the teaching dimension of academia. Finally, I’ll offer suggestions about personal actions one might take based on these two perspectives of an overview of pedagogy and options people take in their career paths.

PEDAGOGY FROM A PERSONAL PERSPECTIVE

The documentation of this journey is personal. I may have missed major pedagogical events and I may highlight ones that others might find trivial. Some of these may no longer have an impact but were pedagogy that provided, for me, important ideas at that time. An asterisk indicates what I consider to be a resource that should be read today or be on your bookshelf.

1. The publication of Bloom’s Taxonomy. This taxonomy is a structured list representing increasing level of difficulty in learning in the cognitive domain. This has been revised by Anderson, et al. Such a classification is extremely helpful in analyzing the degree of difficulty expected in a task. For example, on an exam students should be given a chance to demonstrate an ability to do tasks of varying levels, rather than assigning only tasks at Bloom’s level 6. Similarly, students can use such a taxonomy to monitor their growth. For the affective domain, a similar taxonomy has been developed.

2. McKeachie’s book on Teaching Tips. McKeachie provided the basics for all new teachers (and continues to provide ideas for experienced teachers). The current edition continues to provide great insight on just about any topic.

3. Annual workshops on pedagogy at ASEE meetings by such people as Lois Greenfield, Gus Root, Helen Plants, and Jim Stice. In the 1960s, only a few sessions related to pedagogy were offered by the AIChE. Now, that has changed. Indeed, if we want to interest those faculty whose major concern is research in chemical engineering, then having sessions at the AIChE conference is the way to introduce them to ideas about how to improve teaching. These research-oriented individuals are unlikely to attend ASEE. For those interested in improving student learning we can be inspired by the presentations at ASEE and AERA conferences.

4. In the late 1960s the major event was Ray Fahien’s leadership with Chemical Engineering Education. Ray turned this journal into a major resource for those of us concerned about scholarship in teaching. Keep up-to-date by reading this important publication.

Donald R. Woods is professor emeritus of chemical engineering at McMaster University. He received his B.Sc. from Queen’s University, his M.S. and Ph.D. from the University of Wisconsin, and worked for seven different industries before joining McMaster University in 1964. His research interests are in process design, cost estimation, surface phenomena, problem-based learning, assessment, improving student learning, and developing skill in problem solving, troubleshooting, group and team work, self assessment, change management, and lifetime learning.

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In the ’70s...

5. The McMaster Medical School’s introduction of small-group, self-directed, self-assessed, interdependent PBL started in the late 1960s, with their first class of graduates in 1972. They created their own Center for Teaching (called the Program for Educational Development) that ran frequent “Education Rounds,” published in-house reports, and gave in-house workshops. I was lucky that this occurred on campus, and I could learn details about their approach. But, it wasn’t until 1980 when Howard Barrows and Robyn Tamblyn published *Problem-Based Learning: An Approach to Medical Education* that others had better access to this approach.

The cognitive and psychological basis is summarized by Henk Schmidt and by Norman and Schmidt. This was still limited, however, because for McMaster’s Medical School: a) one admission criteria included performance in a PBL session (whereas students in most programs were admitted based primarily on marks); b) students admitted to the medical school were usually graduates of other undergraduate programs (and were therefore three to four years more mature than our engineering students); c) the whole program was PBL so that one faculty tutor could be assigned to a group of five students (whereas in engineering one faculty member would have a class of about 30 to 100 students); and d) most of the material was developed in the context of health sciences. Hence, attractive as this pedagogical approach might be, major modifications were needed to make it effective in our engineering classrooms. Today, there are many resources to help guide its implementation into different environments.

6. In the late ’60s and early ’70s William Perry published his ground-breaking analysis of *Forms of Intellectual and Ethical Development in the College Years*. It took about 10 years, however, for the impact of this research to take effect. First, the initial approach to helping students understand their “Perry level” required trained professional analysis of essays. It wasn’t until the ’80s when people like Bill Moore established the Perry Network, Dick Culver gave workshops, and Bill Moore, Peggy Fitch, and Joanne Gainen created easy-to-use diagnostic tests that the classroom use of the Perry inventory became more extensive. This inventory helps students (and faculty) identify the attributes the students hold related to the teaching and learning process. For example, students with a Perry level of 2, when placed in a PBL environment, react by saying “the professor isn’t doing his/her job; they are not teaching me.” An inventory more related to developing reflective judgment and critical thinking has been developed by King and Kitchener. Rich Felder’s article “Meet Your Students: 7. Dave, Martha, and Roberto,” *Chem. Eng. Education*, 31(2), 106-107 (Spring 1997), describes three students at different levels of Perry’s Model of Intellectual Development. This can be downloaded from Rich’s Web site.

7. The Ontario University Program for Instructional Development in the 1970s provided financial support for pedagogical projects; they had annual retreats and had external evaluation. In Canada at that time this was a very rare event. The OUPID program was described by Elrick. At that time, we were interested in developing process skills (sometimes called soft, generic, procedural, or higher-order thinking skills) and our research was to learn how best to teach such skills as communication, problem solving, and teamwork. The results from our research were published. In terms of process skills, one of the most challenging pedagogical issues is how best to develop confidence and skill (because lecturing was ineffective) in this domain. Conger’s publications in the late ’60s and early ’70s for the Saskatchewan Newstart Program were an excellent resource.

8. A major key for learning is to have well-written, published learning goals. Mager, Kibler, et al., and Johnson and Johnson provided excellent guidelines as to how to write learning objectives. These guidelines were the basis for developing the Keller plan for Personalized System of Instruction (PSI), or “Individualized Instructional Material.” As an aside, we used their ideas in creating our workshop to develop students’ skill in creating learning objectives as part of self-assessment. This is part of the McMaster Problem Solving Program. Well-written learning objectives are still a critical part of any learning activity. Johnson and Johnson, Kibler, et al., or Mager remain my best resources.

9. Alverno College’s program for the eight abilities. In the mid 1970s Alverno College, Milwaukee, WI, published a list of the eight abilities as outcomes for all their programs. These abilities were effective communication, analytical capability, problem-solving ability, facility in forming value judgments, effective social interaction, understanding of individual/environmental relationships, understanding the contemporary world, and educated responsiveness to the arts and humanities. For each ability they published six goals/learning objectives. They trained students in self-assessment and created a separate assessment office where students could demonstrate their abilities. This revolutionary approach was, and remains, unique. I was lucky enough to be hosted by Dean Austin Doherty who graciously shared materials and helped me see how I could apply some of their approaches at McMaster. Alverno created a separate program-evaluation unit to evaluate the effectiveness of their approach. I would encourage everyone to learn as much about their program as they can by attending their workshops and reading their publications. Their work on self-assessment is superb.

10. In the 1970s, Keller’s personalized system of instruction self-directed learning was a new approach. This prompted workshops, such as Lee Harrisberger’s workshops on Individualized Learning Management or Self-Paced Instruction (e.g., in Ontario such a workshop was held at the University of Guelph in 1974). Background about this approach, and variations on it, continue to be used, and the principles can assist the development of distance-learning modules.
11. A variation of the Personalized System of Instruction was Charlie Wales and Bob Stager’s publications and workshops on Guided Design.[21] They produced a facilitated form of problem-based learning for large groups where autonomous groups of students are given written guided tasks to do. They have created several great resources: two books for freshman engineering courses (including an instructor’s guide) and a guide for new faculty on how to facilitate student learning via guided design. The book is written as a guided-design format. They build their learning process around an 11-step decision-making process. I was fortunate enough to participate in several of Charlie’s workshops, and the published material can be used to help craft PBL activities.

12. Craig Hogan introduced me to his research on Jungian Typology.[22] This inventory provided students with a rich understanding of individual uniqueness and their particular style in learning, deciding, and interacting. This inventory is similar to the Myers Briggs Typological Inventory (MBTI) and the Karsey Bates inventory.[23] We included this as part of the MPS units on Personal Uniqueness and on Learning Skills.[13] I recommend that this be included in all programs as the first step, following Bandura’s model for self-efficacy,[24] in helping students develop self-confidence.*

13. Robert Karplus[25] created workshops including activities to develop reasoning. The activities available are in the subject domains of general science, physics, biology, and chemistry. Again, the pedagogical underpinnings illustrate the use of active learning.

14. Jack Lochhead conferences.[26] In the mid 1970s Jack organized a conference on teaching reasoning, problem solving and critical thinking. He brought together key psychologists and researchers in the area of cognitive thinking (including Dorothea Simon, Jill Larkin, Alan Schoenfeld, Fred Reif, Art Whimbe, John Clement, and Moshe Rubinstein). Fortunately, I was included. This was a very steep learning curve for me because these researchers were using terminology and concepts that were new. It also was a great networking opportunity. I came away with reprints and ideas that provided a strong pedagogical basis for developing problem-solving skills. Additional conferences were held. A recommendation is to interact with colleagues in the cognitive and behavioral sciences and base your in-class interventions on pedagogically sound principles (and not gut feelings).

15. The creation of Centers for Teaching and the gradual introduction of internal grants to support this activity at various universities. Some, like the one at the University of Michigan, were established very early. At McMaster University Drs. Alan Blizzard and Dale Roy, of the Instructional Development Centre, helped me immensely by TV-taping my class and providing gentle feedback, bringing excellent workshop leaders to campus and alerting me to new developments. Frequent your Center for Teaching.*

16. Various newsletters were published on developing problem-solving skills and teaching (the Franklin Institute Press Problem Solving newsletter, McMaster University’s PS News, and the HERDSA newsletter).

17. The Pfeiffer collection of practical workshops to develop soft skills.[27] This is an excellent guide for active workshops on a wide variety of topics. I consult this resource often.

18. The publications of and workshops given by David Boud, Graham Gibbs, and Alan Jenkins that brought a European and Australian perspective. In Canada with the Commonwealth connection, we were fortunate to have visiting educators from the U.K. and Australia who presented workshops.[28]

19. Engineering Practice Introductory Course Sequence, EPICS, program at Colorado School of Mines.

20. AIChE’s subcommittee on Education Projects and the increasing number of sessions from Group 4a at the annual meetings. Jud King’s leadership; Ed Eisen’s annual surveys of “how to teach (subject),” the practice schools. These activities may not have had much emphasis on pedagogy but they provided very useful resources.

21. The creation of the Annals in Engineering Education as a split off from Engineering Education to focus on scholarship.

For the 1980s

22. The Jossey-Bass series New Directions for Teaching and Learning.[29] This excellent series is in most Centers for Teaching and provides easy access to the fundamental research in cognition and behavior upon which to base our efforts.*

23. The creation of the Canadian 3M teaching fellowship program (1984 onwards) had immense impact in Canada. Ten awards are given annually from among 33,000 faculty across Canada in all disciplines. The criteria are effective in-class teaching and scholarship in teaching.

24. Marshall Lih and the NSF programs to financially support educational activities. Again, regrettably Canada does not have such a program.

25. Edward deBono’s book on the Mechanism of the Mind provided good background material for the MPS creativity workshop.[13] His Thinking Course and his workshops were a great resource on how to teach thinking.*

26. Chickering and Gamson[31] summarized cognitive research and suggested that we can improve student learning by applying seven basics: use cooperation not competition, expect student success, have clear time on task, account for your students’ different learning styles, provide prompt feedback, use active instead of passive environments, and have extensive teacher-student interaction.*
27. Felder and Silverman’s learning-style inventory. Rich’s articles “Meet Your Students...” illustrate the implications.

28. The ASEE Summer Schools initially had negligible contributions to pedagogy but recently have included more, for example Rich Felder’s contributions to the Denver Summer School. Throughout the years they have been an excellent source of how to teach different topics.

29. Noel Entwistle and Paul Ramsden’s work on deep, surface, and strategic learning and their development of the Course Perceptions Questionnaire and the Approaches to Studying Questionnaire. Dr. Chris Knapper, of Instructional Development at the University of Waterloo and later at Queen’s University, alerted me to this research and revised the inventories to North American terminology. Rich Felder’s article “MeetYour Students: 3. Michelle, Rob, and Art,” Chem. Eng. Education, 24(3), 130-131 (Summer 1990) describes three different approaches to learning (deep, surface, and strategic), and the conditions that induce students to take a deep approach. This can be downloaded from Rich’s Web site. A new version of the Course Experience Questionnaire has been developed to include process skills.

In the 1990s

30. Karl Smith’s workshops and publications provide the basics for the use of various types of cooperative groups.

31. Wankat and Oreovicz published the excellent text Teaching Engineering. This text can be downloaded free. Consult it often.


33. John Prados and Stan Proctor’s initiative with ABET 2000 criteria. Sadly, the Canadian Accreditation is still a long way off.

34. Web sites: Rich Felder has an excellent Web site from which you can download a rich set of resources. Another excellent Web source is the Society for Teaching and Learning in Higher Education (Canada) STLHE electronic mail forum. Use this forum to pose questions, follow discussions and keep up-to-date.

35. In physics, Hestenes, Wells, and Swackhammer developed an inventory to test a student’s understanding of the concept of “force.” Steif and Dantzler created a concept inventory for statics. Ron Miller, of Colorado School of Mines, has developed three excellent concept inventories related to thermodynamics, heat transfer, and fluid mechanics. Such inventories can be used to evaluate the effectiveness of various learning environments as done, for example, by Hake.

36. At McMaster University several methods are used to recognize an emphasis on improving student learning. These include The McMaster Student Union annual awards for teaching and for lifetime achievement; the President’s Awards for educational leadership, for resource preparation and for in-class teaching; and the Teaching Wall of Fame display. The University of Guelph took the initiative in 2000 to give an honorary D.Sc. for scholarly contributions in teaching and learning. They also have a Visiting Teaching Fellow program. What options does your university offer to celebrate excellence in teaching?

37. John Heywood’s book is a monumental summary of Research and Development in Curriculum and Instruction in Engineering Education. Heywood surveys and critiques papers that have been published in engineering education. Keep this reference book handy for good ideas.

38. The series of five papers on “The Future of Chemical Engineering Education” published in Chemical Engineering Education. Papers 2 and 3 in this series are a convenient summary of ways to improve student learning.

39. The National Survey of Student Engagement, NSSE. This North American survey provides data about: a) the level of academic challenge (based on mainly Bloom’s Taxonomy plus length of assignment); b) active and collaborative learning; c) student-faculty interaction (includes elements of talking to faculty outside of class, receiving prompt feedback, and working on committees with faculty); d) enriching educational experience; and e) supportive educational experiences. Data are given for freshman and for seniors. The 95th and 5th median data are published on the Web for DRU research-intensive universities at three different categories (very high activity, high, and doctoral). Data are also given directly to the participating institutions. The questions can be downloaded so that you could use the same questions to gather data at the course, department, and faculty levels. Extensive norm data are available.

SO WHAT?

1. Your pedagogical journey will be different from mine. However, some common elements will probably include: #1 Bloom’s Taxonomy; #6 Perry’s inventory; #8 how to create learning objectives or goals; #12 and #27, learning-style inventories; #15 draw on the expertise of the professionals in your Center for Teaching; #26 Chickering and Gamson’s seven principles; and #38 the “Future of Engineering Education” series of papers.

2. Base what you do on the cognitive fundamentals. I was lucky to have been invited to Lochhead’s conferences. Otherwise it would have been very difficult for me. Not all of us may be this lucky. So, ideally, attend the AERA conference. Second best is to borrow the Jossey-Bass series from your Center for Teaching. Next, at the AIChE conference we might...
annually sponsor a session on “State of the Art for Learning” to which we would invite three noted researchers from cognitive or behavioral sciences to present one-hour overviews.

3. I’ve noted some resources that you might want to add to your bookshelf. I also think the dual perspective of U.S.-based innovations and Canadian-based innovations is useful. Some are similar but some are not. For example, the 3M and the hon. D.Sc. are, I think, mainly Canadian stuff (that would be nice to see in the United States), and we also have a rich set of workshops (either at our universities or our national STLHE conferences) that draw from the U.K. and Australian connections. On the other hand ABET, NSF funding, AIChe, and ASEE are really strong U.S. elements that I wish we had in Canada.

Consider now some possible career paths.

POSSIBLE CAREERS PATHS

From my experience as a consultant, as a member of the Promotions and Tenure Committee, as departmental and program chair, as expert witness in a law case, and as reference for candidates seeking promotion at a wide variety of universities, I offer five imaginary career paths of individuals. These faculty place different emphasis on pedagogy. Although these are imaginary, they are a relatively realistic snapshot of life for research-intensive universities around 2008. Michelle, Hector, Janice, David, and Frances are from different chemical engineering departments.

Michelle

Michelle focused on chemical engineering research. She tried to be a good supervisor and teacher but her emphasis was on her research. She published about 10 papers/annum and received the most external grants of any of her colleagues. Her research papers won awards. For in-class teaching, her student course ratings were below the average but not disastrous. She never attended any workshops to improve teaching. She was described as “a good solid lecturer.” She had trouble writing a Teaching Dossier but, with the help of her mentor, her dossier was satisfactory.

Michelle was promoted to Full Professor two years in advance.

Hector

Hector’s research in reaction kinetics was going well. He received good grants and some industrial sponsorship. He produced about two refereed publications per year. Hector likes to teach and is rated as one of his department’s better teachers. Active learning is something he uses in all his classes and the students respond very positively. He attends most student events throughout the year. Occasionally visiting faculty from other universities come to talk to Hector about his teaching. Hector attends many of the seminars given by the Center for Teaching.

Hector was promoted to Full Professor on time.

Janice

Janice loved to teach; she really wants her students to learn. As soon as she was granted tenure, she ceased applying for research grants in her specialty of process control and phased out her graduate students. Yes, she continued to be a member of supervisory committees and tried to keep up-to-date with developments in process control. But her focus was on being an outstanding teacher, and outstanding she was. Her students raved about her courses, visitors came to sit in on her classes, she won numerous student teaching awards for her in-class teaching. Her skill seemed to come naturally; she rarely consulted with colleagues in the Center for Teaching nor did she attend conferences or read educational journals.

Janice remained an Associate Professor for all her career. Indeed, she was encouraged to assume a heavy teaching load because “the students love her.”

David

David was a terrific performer in class. “Spellbinding,” “fun,” “tops in entertainment and you learned too”—these are some of the student accolades. He annually won the top awards from the students. David frequents the Center for Teaching and gives many popular workshops. He publishes papers describing teaching tips, approaches he uses in the classroom, and how to interest students in any topic. The paper are published in refereed journals.

In addition, David has a research group in nanotechnology. He receives good funding and usually has one master’s and one Ph.D. student.

When David was considered, “on time,” for promotion to Full Professor the committee turned down his promotion because “we normally expect 10 refereed publications. David has five refereed in nanotechnology. He also has five papers in education, but in neither field—nano or education—does David have a full 10.

Frances

Francis loves to teach and wants to measure the effectiveness of her classroom interventions. She also is a skilled researcher and decided to apply her research skills to teaching. She selected cooperative learning and self-assessment as her two areas of specialization.

After she attended Karl Smith’s workshops at an ASEE meeting, she returned to campus and immediately introduced cooperative learning into both her undergraduate and graduate courses. Her student evaluations plummeted. In consultation with the Center for Teaching she realized that, when introducing new approaches, she needed to rationalize the choice to the students, and use class ombudspersons to continually monitor the quality of the teaching-learning team. Subsequently her student ratings increased dramatically. Frances is rated one of the better teachers in the department. To evaluate the effectiveness of her methods she gathered pre- and post-data using Miller’s concept inventories and compared her results.
with the performance of students in conventional lecture classes. She also gathered data from the Course Perceptions Questionnaire and from NSSE. Frances publishes about three refereed papers/annum about her research-in-teaching. She receives grants from NSF to support her educational research. Her scholarly papers have won awards, and she is frequently asked to give seminars about cooperative learning or about self-assessment.

Frances’s case for promotion to Full Professorship has been delayed for two years. In discussing this with the provost the provost admitted that the P&T committee has difficulty assessing the quality of the refereeing system used by the educational journals in which she published. “We know about Chemical Engineering Science and about the AIChE Journal but how rigorous are journals like Assessment and Evaluation in Higher Education? The committee will reconsider your case next year.”

SO WHAT?

In summary from these cases, most institutions are research-oriented and know how to measure effectiveness in chemical engineering research. P&T committees, and administrators tend to be learning about, but remain unconvinced and uncertain about, research-in-teaching. We need to demonstrate that refereed journals, such as Assessment and Evaluation in Higher Education, are equivalent in reviewing standards to Chemical Engineering Science, for example. More details on how faculty and administrators might address the issues raised in these cases are available.\[34\]

Faculty are learning that research-in-teaching requires well-designed evaluation of pedagogical interventions. In the past we have incorrectly tended to use “they liked it” and “I liked it” evaluation. We tended to “diddle around” trying different things in the classroom without evaluating their effectiveness. We published refereed papers describing what we did in the classroom, as David did, instead of measuring the effectiveness. We should apply our well-developed research skills to evaluate our approaches to teaching.

SUMMARY

From this view of activities in different countries, the evolution of a rich set of pedagogical ideas and a brief look at career paths of persons placing different emphasis on pedagogy, here are my top three recommendations.

1. Personal, starts with you. You can have a major impact.
2. Look beyond the United States, beyond AIChe and ASEE, and learn from what others have done. Arrange a three-day visit with educators in your area of specialization. Visit your Center for Teaching often.
3. Have a realistic understanding of your local P&T system; if you don’t get tenure you can’t teach.

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Chemical Engineering Education
Integrating Modern Biology Into the ChE Biomolecular Engineering Concentration Through a CAMPUSWIDE CORE LABORATORY EDUCATION PROGRAM

SUSAN CARSON, JOHN R. CHISNELL, AND ROBERT M. KELLY
North Carolina State University • Raleigh, NC 27695-7905

Efforts to infuse modern life sciences concepts into the traditional chemical engineering curriculum have accelerated in recent years, giving rise to a “new” sub-discipline, often referred to as biomolecular engineering. Chemical engineering programs worldwide have embraced biomolecular engineering to the point that many departmental names now include this (or a similar) moniker, reflecting a commitment to a permanent evolution of the discipline in this direction. One might argue that we have been here before (i.e., biochemical engineering), but the professional and technological driving forces to embrace biology within engineering have never been stronger. Our students are very interested in how biology fits into the chemical engineering “genotype” and how to prepare themselves for professional opportunities in the biotechnology arena. As a result, the task before us is to train students to function at the interface between chemical engineering and modern biology so that they can contribute to new emerging technologies ranging from biopharmaceuticals to biomaterials to bioenergy.

Truth be told, emphasis on the molecular life sciences (and other molecular sciences as well) has revitalized chemical engineering and should ultimately reinvent the discipline in many ways.11 With all this excitement, however, comes a significant challenge—how to modify chemical engineering education so that its critical underpinnings are not slighted while, at the same time, going beyond a superficial treatment of the molecular life sciences. In other words: Can a ChE “educational genotype” be developed that intrinsically and seamlessly integrates the life sciences? This experiment is being currently being run at many institutions and requires rethinking of how chemical engineers are trained. To this end, many creative modifications of the undergraduate curriculum have been proposed and implemented to include elements of biology. A major shortcoming typically arises, however: Given the strong emphasis on sophisticated laboratory skills associated with the molecular biosciences and the lack of suitable lab courses and facilities on most campuses to deliver
such training, how can an effective laboratory component be included? This is actually an issue not only for chemical engineering departments, but also for life sciences disciplines that need to provide up-to-date, laboratory-based training in modern biology for their students.

CORE LABORATORY TRAINING IN MOLECULAR BIOTECHNOLOGY

The expensive and sophisticated nature of laboratory techniques used in molecular biotechnology presents a challenge to those charged with developing pertinent instructional programs. In most cases, training along these lines on university and college campuses happens in a highly decentralized way: college-by-college, department-by-department, or—for graduate students—research-lab-by-research-lab. These approaches seem to work at some level, but they suffer from several potential problems:

- The required effort and expense to carry out such training for particular programs can be prohibitive and, in the end, the results may be ineffective.
- In research labs, student-to-student “instruction” can propagate incorrect methodologies in addition to the fact that equipment, materials, and supplies intended for research can be wasted as a consequence of the “learning curve.”
- In isolated settings, interdisciplinary communication about new developments and advances in biotechnology techniques may not happen. Given the expanding array of disciplines, including biomolecular engineering, that can benefit from molecular biotechnology skills, decentralized training efforts will fail to capture this potential.

In any case, more effective strategies are needed to offset inadequate training in the range of lab skills associated with molecular biotechnology.

At North Carolina State University (NCSU), a core laboratory facility has been established and operates through its Biotechnology (BIT) Program (<www.ncsu.edu/biotechnology>) to teach molecular biotechnology skills to students campuswide. This core facility was originally made possible by a unique funding arrangement between the colleges whose students benefited from the courses offered. Staffing was funded through a codicil between five colleges: Agriculture and Life Sciences, Engineering, Veterinary Medicine, Natural Resources, and Physical and Mathematical Sciences. The laboratory instrumentation and expendable supplies are covered through an allocation from a campuswide educational technology fee, which allows the core facility to provide instruction in a modern laboratory setting with provision for continuous updating of instrumentation. The overarching philosophy of the NCSU BIT Program is that molecular biotechnology encompasses a spectrum of theoretical knowledge, skills, and lab techniques needed for advances in modern life science research and technology. Molecular biotechnology is not an end in itself but rather a means of solving problems, unraveling mechanisms, and developing new technologies with societal benefit. The NCSU BIT Program is committed to enriching the base of scientific knowledge and laboratory skills necessary for genetic manipulation of living things at the molecular level. It also requires students to address the ethical issues surrounding biotechnology so that they can decide for themselves whether the merits of these new capabilities outweigh the associated risks.

CAMPUSWIDE PARTICIPATION IN THE NCSU BIT PROGRAM

The NCSU BIT Program currently trains approximately 300 graduate and undergraduate students (as well as some postdocs, technicians, and faculty) annually, coming from over 35 departments and programs campuswide. The BIT courses are very popular, and most sections fill each semester. From Fall 2001 through Spring 2008, there have been more than 2,300 enrollments in BIT courses, representing students in most of the colleges at NCSU (see Table 1). Nonmatriculated students

<table>
<thead>
<tr>
<th>COLLEGE</th>
<th>Lab Course Enrollments</th>
<th>TOTAL</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Graduate</td>
<td>Undergrad.</td>
<td></td>
</tr>
<tr>
<td>Agriculture and Life Sciences</td>
<td>637</td>
<td>540</td>
<td>1177</td>
</tr>
<tr>
<td>Engineering</td>
<td>142</td>
<td>454</td>
<td>596</td>
</tr>
<tr>
<td>Lifelong Learning</td>
<td>142</td>
<td>16</td>
<td>158</td>
</tr>
<tr>
<td>Veterinary Medicine</td>
<td>127</td>
<td>0</td>
<td>127</td>
</tr>
<tr>
<td>Physical &amp; Mathematical Sciences</td>
<td>23</td>
<td>36</td>
<td>59</td>
</tr>
<tr>
<td>Natural Resources</td>
<td>24</td>
<td>3</td>
<td>27</td>
</tr>
<tr>
<td>Textiles</td>
<td>7</td>
<td>6</td>
<td>13</td>
</tr>
<tr>
<td>Humanities &amp; Social Sciences</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Management</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Graduate School</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1,105</td>
<td>1,063</td>
<td>2,168</td>
</tr>
</tbody>
</table>

1 Does not include 176 enrollments in lecture courses
2 76% of graduate and 93% of undergraduate from ChE
3 Represents 1,239 different students from 39 departments in 10 colleges
may take courses through Lifelong Education (LLE); in fact, part-time students currently employed in North Carolina’s Research Triangle Park (a high-technology research and development center housing more than 170 companies) are a growing component through a certificate program. For graduate students, not surprisingly, 55% of enrollments have been from the College of Agriculture and Life Sciences (CALS), but approximately 17% came from the College of Engineering (COE). Among undergraduates, approximately 50% of enrollments were from CALS and 43% were from COE. The overwhelming majority of students from COE were from the Department of Chemical and Biomolecular Engineering, at both the graduate (76%) and undergraduate (93%) levels.

**ACADEMIC FRAMEWORK FOR MOLECULAR BIOTECHNOLOGY EDUCATION**

While students can enroll in specific BIT courses to meet educational or research objectives, training in molecular biotechnology is officially recognized through campuswide academic minors and a certificate program. These are described below in brief:

**Undergraduate biotechnology minor:** Open to all NCSU undergraduates, across all colleges, and all majors (see Table 2). The Department of Chemical and Biomolecular Engineering has developed a biomolecular engineering concentration, which embeds this biotechnology minor into the B.S. degree. In addition to the normal ChE classes and BIT minor, students also take an introductory biology course (which replaces a chemistry elective), Biochemistry (which replaces quantitative chemistry), and a course in capstone biochemical/biomolecular engineering to complete the concentration. To make space for the concentration in the curriculum, two elective BIT modules taken for the minor can be substituted for the second semester of unit operations lab, and a semester-long, undergraduate research experience is counted as a technical elective.

**Graduate biotechnology minor:** Open to all NCSU master’s and doctoral degree candidates that have taken appropriate prerequisite courses and whose thesis research is in an area of molecular biotechnology (see Table 2). In addition to learning molecular biology techniques through lab courses, students have a unique opportunity to interact with peers in various disciplines. This has led to interdisciplinary research collaborations between groups on campus that may not have otherwise occurred. The interesting thing is that these have been student-driven. For example, food scientists working with veterinary medicine students to develop novel drug delivery methods and chemical biology and chemical engineering

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
<th>Undergrad Minor</th>
<th>Graduate Minor</th>
<th>Graduate Certificate</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Biology (or equivalent)</td>
<td>Introductory biology course that includes coverage of gene regulation (i.e., lac operon).</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Organic Chemistry</td>
<td>Two semesters of organic chemistry</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Manipulation of Recombinant DNA (Core Course)</td>
<td>Intensive molecular cloning laboratory course (undergraduate level)</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Core Technologies in Molecular and Cellular Biology (core)</td>
<td>Intensive molecular cloning laboratory course (graduate level)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Advanced biotechnology laboratory modules</td>
<td>Students choose from courses described below</td>
<td>X (2)</td>
<td>X (1)</td>
<td>X (2)</td>
</tr>
<tr>
<td>Research experience</td>
<td>150 hours of biotechnology research on campus or other molecular biology-related research (academic, government, or industrial)</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Thesis or dissertation</td>
<td>Thesis or dissertation research must utilize molecular biotechnology skills</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Faculty representative</td>
<td>At least one member of the student’s thesis/dissertation committee must be a member of the Biotechnology faculty</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Lecture electives</td>
<td>Upper-level lecture course covering molecular biology topics; Examples: Prokaryotic Molecular Genetics, Plant Molecular Biology, Biochemistry of Gene Expression, Genetic Data Analysis, Functional Genomics, and Biochemical Engineering</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Ethical Issues in Biotechnology</td>
<td>Ethics and real-world issues in biotechnology and professional ethics</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
students developing novel ways to do microwave-driven biocatalysis. Such interactions would likely not have occurred without the BIT program.

**Graduate certificate program in molecular biotechnology:** Instituted in 2005 to provide post-baccalaureate students with the opportunity to obtain university-recognized credentials in molecular biotechnology, this certificate program is primarily geared toward nontraditional students who have already entered the workforce or are seeking to re-enter the workforce. For example, it provides an excellent opportunity for traditionally trained, practicing chemical engineers to gain expertise in molecular biology lab skills. NCSU graduate students who are not eligible for the graduate minor because their thesis/dissertation work is not in an area of biotechnology are also eligible for the certificate program. Participating students must have completed all prerequisites (or equivalent) to a “Core Course” (described below) before acceptance to the certificate program. The minimum requirements for the Core Course are a general biology course that covers gene regulation and DNA replication, and two semesters of Organic Chemistry. A general microbiology course is recommended but not required. Prerequisites for the coursework electives vary, and those prerequisites may be taken after admission to the certificate program, if necessary. Requirements for completion of the graduate certificate program are detailed in Table 2.

**WHAT COURSES ARE OFFERED?**

All students begin the program by taking a course entitled: Core Technologies in Molecular and Cellular Biology. This Core Course is a four-credit course offered annually in both Fall and Spring semesters, covers the basics of methods in recombinant DNA and protein expression, and serves as the prerequisite for all of our other courses. It is a semester-long class that meets each week for a two-hour lecture and a five-hour lab. Students completing this course are awarded our annual BIT Program T-shirt. These usually are designed around one of our new modules and have slogans, such as “BIT happens” or “get bit” (see Figure 1). Following completion of the Core Course (or demonstrating prior equivalent training), students can take advanced laboratory courses, referred to as “modules,” which have the same weekly two-hour lecture, five-hour lab periods, but are only two credits and last only one-half semester. Students are able to mix and match modules according to their interests. Most of these have only the Core Course as a prerequisite — this structure creates sufficient flexibility for students campuswide to pursue the graduate and undergraduate minors. Most of the courses are offered at both graduate and undergraduate levels. In general, students who take courses for undergraduate credit are expected to master techniques and concepts covered in the course, and to be able to analyze data and troubleshoot experiments gone awry. Students taking the courses for graduate credit have the additional expectation of being able to develop their own experiments and protocols in the area covered in the course. Advanced undergraduates are able to take graduate-level courses by special permission. Brief descriptions of course content are provided in Table 3.

**WHO TEACHES THE LAB COURSES?**

Since we are a program, and not a department, one of the most common questions asked of us is: “Who teaches these courses?” The answer is that instructors are recruited from across campus and are at different career stages, but they have certain things in common: 1) they are volunteers and
not required to teach our classes; 2) they have expertise in the area of instruction, both conceptual and at the bench; and, 3) they have a strong desire and ability to teach sophisticated modern biology lab techniques effectively. The majority of our instructors are tenured or tenure-track faculty from a variety of departments and colleges. Their home departments receive "credit hours taught" for the classes they offer, thus the instructors' department heads are typically supportive of

| TABLE 3 |
| Course Offerings in NCSU Biotechnology Program |

| Core Technologies of Molecular and Cellular Biology* | Sub-cloning a gene into an expression vector; screening for positive transformants by a variety of methods including DNA preparation, ligation and transformation, PCR, restriction mapping, colony hybridizations with DNA and monoclonal antibody probes, SDS-PAGE, and Western blotting; and purification of recombinant protein by affinity chromatography. |
| RNA Interference and Model Organisms | History and application of RNAi technology; design of experiments to silence gene expression in various organisms; assessing extent of silencing; use of online tools for design of RNA silencing constructs to knockdown mammalian protein expression; advantages and disadvantages of model organisms; proficiency using Nicotiana benthamiana tobacco plants, Caenorhabditis elegans, and mammalian cell culture. |
| Phenotypic Analysis of Transgenic Plants | Phenotypic parameters that can be measured to characterize a mutant or transgenic plant line; methods and technologies that can be used for these characterizations. |
| Genetic Engineering of Eukaryotic Microbes | Importance of filamentous fungi and yeast in biotechnology and as research tools; manipulation and growth of these eukaryotic organisms "in vitro"; genetic transformations of fungi; creation and analysis of mutant strains; expression of heterologous proteins in yeast. |
| Fermentation of Recombinant Microorganisms | Small-scale fermentations of recombinant Escherichia coli and Saccharomyces cerevisiae; factors affecting gene expression and protein production. |
| Protein Purification | Chromatography techniques for protein purification, including ion exchange, hydroxyapatite, hydrophobic interaction, gel filtration, affinity; purification tables constructed based on SDS-PAGE analysis, enzyme assays, and protein concentration. |
| Protein-Protein Interactions | Basic concepts and techniques involved in the study of protein-protein interactions, including the yeast-2-hybrid system, pull-down assays, and immunoprecipitation. |
| Proteomics | Introduction to the theory and practice of proteomics, analysis of microbial proteomes, statistical data analysis, MS fundamentals. |
| Mutagenesis | Site-directed mutagenesis by a variety of methods in multiple organisms. |
| Plant Tissue Culture and Transformation | Basic techniques in plant tissue culture and transformation in model plant species and agriculturally important plants. |
| Animal Cell Culture Techniques | Culture of embryonic stem cells; establishment and maintenance of large-scale eukaryotic cell culture for protein production. |
| Advanced Animal Cell Culture | Culture of embryonic stem cells; establishment and maintenance of large-scale eukaryotic cell culture for protein production. |
| Genome Mapping | Basic techniques in genetic and physical mapping; principles of DNA marker development, marker detection, genetic and physical mapping; DNA sequencing. |
| DNA Microarrays | Array design and printing; principles of data analysis and data mining using data acquired from actual experiments; importance of controls and statistical significance; global controls of gene expression. |
| RNA Purification and Analysis | Isolation of RNA and quantification by spectrophotometry; and analysis by gel electrophoresis; northern blotting and non-radioactive labeling and detection by chemiluminescence. |
| Real Time PCR | Real-time PCR theory, techniques, machinery, troubleshooting, tools, and advanced protocols, such as multiplexing and SNP analysis. |
| Ethical issues in Biotechnology ** | Discuss and debate controversial topics in biotechnology. |
| Computer Analysis of DNA Sequences ** | Databases (particularly NCBI/GenBank) for finding homologs of genes and proteins of interest; tools commonly used in DNA analysis software packages. |
| Research Ethics ** | Seminar/discussion of research ethics topics including authorship, animal/human subjects, bioethics, intellectual property, and research fraud. |
| Capstone Biotechnology ** | Molecular biotechnology-related research seminars by academic/industrial speakers; stock market competition; interdisciplinary group design project. |
| Professional Development ** | Seminar/discussion of topics related to career development, including public speaking, grant writing, CVs, postdoc opportunities, attending scientific meetings, interviewing skills. |

* Manipulation and Expression of Recombinant DNA: A Laboratory Manual, 2E, was developed for this course (1)
** Lecture format only

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the arrangement. Some of our instructors are research faculty members or research associates. These are individuals with doctoral degrees whose appointment at the university is primarily research but who have interest in developing their teaching skills to prepare them for academic appointments. They teach courses on a semester-by-semester basis and we “buy” some of their time to be dedicated to instruction. We also have one teaching assistant professor whose appointment is to teach for the Biotechnology Program and to serve as academic coordinator. Finally, we employ one to two teaching postdoctoral fellows (see below).

This instructional model has allowed us to maintain instructors with a high level of energy, expertise, and enthusiasm. One of the benefits to teaching in our program is that all of the students are there because they want to be, thus creating a very stimulating educational environment. Graduate teaching assistants are typically recruited from the labs of the instructors — these are the people who use the techniques and technology on a daily basis and bring a very positive and essential element to the courses. Course evaluations are routinely very positive — no doubt the product of interested instructors and teaching assistants teaching interested students.

CHALLENGES FACING CAMPUSWIDE LABORATORY INSTRUCTION

Campuswide programs focusing on life sciences face some unique challenges due to their interdisciplinary nature. Discussed below are some that we have faced.

Prerequisites: In a given class in the NCSU BIT Program, we have students from majors ranging from chemical engineering to plant biology to textiles to microbiology to veterinary medicine. Because we are a campuswide core laboratory education facility and our mission is to train students from diverse disciplines, it is critical that the prerequisites for our courses be sufficient but not restrictive. The only prerequisites to our Core Course are a freshman-level Biology course that covers DNA replication, transcription, and translation at a very basic level, and a chemistry course through the second semester of organic chemistry (two semesters of General Chemistry and two of Organic). While almost all of our students ultimately take Biochemistry, this may not occur before they take our lab courses. For this reason, background knowledge varies considerably from student to student. Despite this potential problem, the courses have gone surprisingly well. Learning to appreciate how other disciplines approach technical issues can be an education in itself.

Clicker technology: Students with engineering backgrounds tend to have an easier time with quantitative aspects, while students from life sciences majors, such as microbiology and genetics, typically have a better background in biological concepts. We have worked to overcome these differences in a variety of ways. One method we have used in the classroom is the implementation of clicker technology. Interspersing “clicker questions,” which the students answer by hand-held devices, throughout each lecture in our Core Course allows students to work through questions on their own, without the risk of one student calling out the answer before each student has a chance to think it through. It also helps students not understanding a concept to weigh in on the pace of the instruction without fear of being embarrassed by asking a “simplistic” question.

Aseptic technique: In a given semester, perhaps half of the students in the Core Course have already had Microbiology Lab (or Cellular Biology Lab), and thus only about half have developed skills in aseptic technique. Time is limited in our core course so that proper coverage of aseptic technique at the level that it is covered in Microbiology or Cell Biology labs is not possible. We overcome this limitation by assigning students to lab groups of two, each with a different major; students without previous experience in aseptic methods often learn this from their lab partner. By limiting lab groups to two students, significant participation is expected from everyone.

Graduate/undergraduate mix: Almost all of our courses are dual-level courses, with undergraduate and graduate students in the same classroom and lab. Because many of our courses are resource-intensive “boutique” courses, and because undergraduates and graduate students are seeking to acquire the same set of skills, it makes sense from a budgetary standpoint to combine the levels to reap the greatest benefit from the equipment available. Generally, the students in the graduate- and undergraduate-level courses have the same lectures and the same laboratory exercises. As mentioned previously, however, the graduate students are expected to perform at a higher level of understanding and proficiency than the undergraduates, as assessed by special assignments given to the graduate students. For example, all students would be expected to apply concepts to solve problems, troubleshoot experimental problems, and analyze data, but graduate students might be expected to write a mini-research proposal, design experiments from start to finish, or critically evaluate a journal article for its scientific merit. Although we had initial concerns about grouping graduate and undergraduate students, we have not experienced any significant problems in delivering our courses — not surprising since the lab skills being taught are typically new to everyone.

NEW AND CONTINUING INITIATIVES

The core laboratory education model has also served as a nucleation point for many campuswide efforts that go beyond our instructional program and as a test bed to try new things that would not be possible in a typical departmental setting. Some examples of such activities are discussed below.

Undergraduate research: There is little doubt that direct involvement in research greatly enhances the undergraduate educational experience. The process of researching a topic
in the primary literature, designing experiments, implementing those experiments, and analyzing the results is critical for developing the analytical skills necessary to function in the biotechnology sector. To earn the undergraduate biotechnology minor, students must participate for at least one semester of research on a molecular biotechnology-based project or work for a period of time with a biotechnology company. With respect to the latter, NCSU’s proximity to Research Triangle Park allows ample opportunity for such experience. We also have two new initiatives directed at enhancing the undergraduate research experience.

First, partnering with the Department of Plant Biology at NCSU, we operated an NSF Research Experience for Undergraduates (REU) grant in the area of synthetic biology in plant systems. The program, which commenced in Summer 2009, allowed students from universities outside of NCSU to pursue summer research experiences on our campus. All students in the summer program first completed “biotech boot camp,” an accelerated, intensive version of our Core Course, so that they gained the proper skills to work effectively in the labs they chose to join on campus for the summer. We think that this preparation will make the REU experience better for both students and mentors since some preparation in molecular biology skills preceded their laboratory experience.

Second, we are working with the Howard Hughes Medical Institute Science Education Alliance (HHMI SEA) to develop and implement a first-year inquiry-guided course. In the proposed course, students will isolate naturally occurring bacteriophage (viruses that infect bacteria, but not humans) from the environment. They will culture, isolate, and titrate the bacteriophage (phage), then visualize the phage by transmission electron microscopy, and purify its genome. One of the phage isolates will be sequenced, and in the second semester of the course, the first-year students will assemble and annotate the genome. The culmination of this project will be to submit novel sequence to Genbank and prepare and present a poster for our annual campus Undergraduate Research Symposium. Our goal is to have students experience the scientific process firsthand early in their college education. This course would be open to students in all majors, with no college-level prerequisite. For non-science/engineering majors, the understanding of the scientific method may be more valuable than the facts they could learn in a traditional lecture course. For science or engineering majors, we anticipate that involvement in research projects will enhance their performance in science curricula, and will give them confidence to pursue more independent research earlier in their academic careers.

Teaching postdocs: We also have implemented a Teaching Postdoctoral Fellow Program. This is a “win-win” program that gives recent Ph.D. graduates, preferably with a conventional postdoc experience already completed and with a strong interest in an academic career, the opportunity to gain significant mentored teaching experience. Since the fellows come “fresh off the bench” with experience in the most cutting-edge technologies, they add an innovative dimension to our program. This fellowship allows for the postdoc to teach a section of the Core Course under the mentorship of an experienced instructor, and then develop and implement his or her own specialized half-semester course. We have “graduated” two teaching postdocs to date, and are working with our third. The two postdocs who completed the program have successfully acquired faculty positions at primarily undergraduate institutions. The new courses that have been added to our curriculum through this program are Mutagenesis, RNA Interference and Model Organisms, and a new course in Protein-Protein Interactions. Graduate and Undergraduate Training: The Biotechnology Program also oversees two externally funded training programs at NCSU and contributes to several others. At NCSU, we have an NIH T32 Biotechnology Training Grant as well as a Department of Education Graduate Assistance in Areas of National Need (GAANN) Fellowship Program in Molecular Biotechnology. Graduate students supported by these awards complete the graduate Biotechnology minor as well as benefit from other courses that we offer. A new NIH Training Program in Translational Medicine in the Veterinary College will also use elements of our courses for their students. The Microbial Biotechnology Master’s program in the Department of Microbiology, which has a strong business focus, incorporates our molecular biology lab courses into their programs. Undergraduate students receiving biomanufacturing training at NCSU through the new Golden LEAF Biotechnology Training and Education Center (BTEC) and the Bioprocessing Science (BBS) major in the Department of Food, Bioprocessing, and Nutrition Sciences integrate offerings from the BIT Program into their curricula. Other programs and departments on campus are encouraged to use our coursework to leverage the campuswide investment at NCSU in molecular biotechnology training.

LESSONS LEARNED

Because our program has significantly expanded since 2001, we have learned several important lessons about delivering interdisciplinary courses to multidisciplinary groups of students.

Faculty have a much bigger problem with interdisciplinary learning in a multidisciplinary setting than do students. It has been clear that the students in our program have adapted well to the unique educational environment.

One of the benefits to teaching in our program is that all of the students are there because they want to be, thus creating a very stimulating educational environment.
Since they spend five hours per week in a lab setting, there is ample opportunity for them to interact with their lab mates (as mentioned above, we try to pair students from different majors in lab groups) and to appreciate elements of other disciplines. This results in some creative approaches to experiments and data analysis. They are more open to new ideas and new approaches.

Well-taught lab courses in modern biology can have an important positive impact on campus research productivity. Graduate students in our program can take lab classes that help them to quickly get up to speed in new methods and techniques that can have a significant impact in their research labs. For one thing, the barrier to “pioneering” new directions can be minimized. Faculty can incorporate the latest approaches into their projects and proposals since their students have easy access to advances in molecular biotechnology through lab courses taught by experts.

It is important to minimize prerequisites so that students can fit extra classes into already busy curricula. The broader the reach across campus, the more complex it becomes to accommodate the range of curricula impacted by interdisciplinary courses. If the prerequisite threshold can be kept low, more students can fit new programs/courses into their plans. This is no doubt a challenge but one that has not been as daunting as first expected.

When delivering optional educational programs, remember that students will vote with their feet. Interdisciplinary courses are often “extra” to students’ home department curricula. If not taught well, students will not be interested in taking them. It is important to keep in mind that the classes are not being taught to “captive” audiences, as is the case for required courses.

The only constant in modern biology laboratory education is constant change. In modern biology, lab methods and techniques evolve rapidly, as does instrumentation. Be prepared to continuously update courses to keep abreast of the field. This requires financial commitment as well as commitment from instructors to incorporate new developments.

ChE can take a campuswide leadership role in molecular biotechnology. Molecular biotechnology can be viewed as a bridge between the fundamental life sciences and biomaterials. Chemical engineers can play an important role in linking these two elements, given their focus on molecular sciences and technology. Given this broad perspective, ChEs can catalyze efforts to bring molecular biotechnology skills to campus science and engineering communities.

SUMMARY

Thinking “outside the box” can sometimes lead to interesting educational outcomes. Though not without unique challenges, a campuswide core educational program at NCSU has proven to be an efficient and effective way to deliver cutting-edge molecular biotechnology laboratory courses to students from a wide range of disciplines, including chemical and biomolecular engineering. Housing expensive equipment in a single facility where it can be taken full advantage of, rather than duplicating equipment for teaching purposes in multiple departments, has been a clear advantage in the current budget climate. Furthermore, unforeseen opportunities, such as student-driven interdisciplinary collaborations, have arisen. We encourage other institutions to investigate whether this model will work for them and are happy to discuss our experiences with anyone who is interested.

With respect to integrating molecular biosciences into chemical engineering (the new “ChE genotype,” if you will), laboratory training at sufficiently sophisticated levels that reflect state-of-the-art techniques and skills is crucial. While it may be infeasible for chemical engineering departments to provide this training on their own, partnerships campuswide can not only provide such opportunities but also create a new paradigm for training our students in the molecular sciences. As we re-think ChE curricular design with biology in mind, it must be done with an eye towards the world of science and technology that our students will be entering: one that is interdisciplinary and dynamic, and one that will care not only about what they know but also what they can do.

ACKNOWLEDGMENTS

Financial support for the BIT Program is provided by the NCSU Provost’s Office. We also thank Dr. Ken Esbenshade in the College of Agriculture and Life Sciences for administrative support.

REFERENCES

With the substantial investment into the development of nanotechnology infrastructure for the 21st century and beyond, there is a need to adapt engineering and science curricula to equip students with the skills and attributes needed to contribute effectively in manufacturing-based processes that rely on nanotechnology.\cite{1,2,3} The incorporation of nanotechnology into the undergraduate engineering curriculum represents both an opportunity and a challenge.\cite{4} On the one hand, nanotechnology can revitalize undergraduate programs by engaging students with interesting nanotechnology-related concepts, examples, and experiments. On the other hand, due to its inherent interdisciplinary nature, programs will need to accommodate greater degrees of interdisciplinary teaching and research. Chemical and biological processes will play a significant role in the manufacturing operations. Chemical and biological engineers have the advantage of a solid background in chemical kinetics, reactor design, transport phenomena, thermodynamics, and process control to undertake the challenges in the high-volume manufacturing of nanotechnology-based products. Thus, these processes fall well within the purview of chemical and biological engineering undergraduate programs. At the same time, however, the products rely on principles based on other disciplines such as physics, mechanical engineering, and electrical engineering. Thus research and development of new processes based on new products is inherently interdisciplinary in nature. Chemical and biological engineers

Milo D. Koretsky is an associate professor in the School of Chemical, Biological, and Environmental Engineering at Oregon State University. He received his B.S. and M.S. degrees from UC San Diego and his Ph.D. from UC Berkeley, all in chemical engineering. He currently has research activity in areas related to thin film materials processing and engineering education and is interested in integrating technology into effective educational practices and in promoting the use of higher-level cognitive skills in engineering problem solving.

Alex Yokochi is an assistant professor in the School of Chemical, Biological, and Environmental Engineering at Oregon State University. He received a B.S. and M.S. from Southern Illinois University at Carbondale and Ph.D. from Texas A&M University, all in chemistry. His research and teaching interests include the development of methodology to produce large volumes of engineered nanoparticles with well-defined size and/or composition for various applications.

Sho Kimura is a professor in the School of Chemical, Biological, and Environmental Engineering at Oregon State University. He received his B.S. and Ph.D. degrees from Osaka University, Japan, and M.S. degree from Oregon State University, all in chemical engineering. He teaches Material Balances and Stoichiometry, Material and Energy Balances in Nanotechnology, and Chemical Plant Design I & II. His research interests include syntheses of carbon and silicon carbide nanotubes.
will also play a vital role in this development as nanosystems evolve to include active nanostructures, 3-D nanosystems and systems of nanosystems, and heterogeneous molecular nanosystems.\cite{5} The curricular challenge that needs to be addressed is how to design a program that reinforces the ChE undergraduate’s core skills (depth) in a way that can be applied toward manufacturing nanotechnology-based products while simultaneously providing the breadth to interact effectively on the multidisciplinary teams that span the wide range of opportunities enabled by this emerging area.

It has been proposed that as the chemical engineering profession takes its next evolutionary step toward applying molecular scale engineering to a set of new and emerging technologies, the core undergraduate curriculum needs associated reform.\cite{5} As topics from these emerging molecular-based technologies are incorporated, however, there is a legitimate concern of dilution of the core content due to staffing issues.\cite{6}

At Oregon State University (OSU), the Chemical, Biological, and Environmental Engineering programs have recently joined into a single administrative structure. This structure alleviates the staffing issue in two ways. First, a significant portion of the courses for all three programs is jointly taught. This set of 11 core courses covers fundamentals germane to all three disciplines (e.g., material and energy balances, transport processes, thermodynamics, and process data analysis) while reducing the number of instructors needed. Second, the Option areas in chemical engineering are taken from topics that have core research faculty. In two of the Options, biological processes and environmental processes, chemical engineering students take elective classes from among those offered by the other programs. In this way, some of the key elements identified in the “New Frontiers in Chemical Engineering Education” workshops are integrated into the undergraduate curriculum while, simultaneously, holding students accountable for the same depth of learning that has served OSU ChE graduates for many years. Moreover, this integration is accomplished in a reasonable scope commensurate with the resources of the program.

This paper presents the curriculum developed to incorporate nanotechnology education in the chemical engineering program at Oregon State University. The approach is twofold: 1) to develop a Nanotechnology Processes Option in the Chemical Engineering Program and 2) to develop two new sophomore-level courses: a survey course that is broadly available to all engineering undergraduates and a discipline-specific laboratory course that allows students to synthesize the engineering science content toward the application of nanotechnology. The curricular development fits in well with the growing research and commercialization activity of the Oregon Nanoscience and Microtechnologies Institute (ONAMI), and is consistent with the evolutionary vision developed by leading chemical engineering educators in the three-workshop series “New Frontiers in Chemical Engineering Education.”\cite{5}

### Nanotechnology Processes Option In Chemical Engineering

To meet all the ABET engineering topics and advanced science requirements, ChE students are required to take five to six technical elective classes outside the ChE core. These courses may be taken in any area as long as they have the appropriate engineering or science content as prescribed by ABET and AIChE. When taking the courses in an ad hoc manner, however, students have indicated that they get little satisfaction or career enhancement. The ChE Department has established Options to aid students in selection of elective courses. Options also help to broaden and strengthen the undergraduate ChE curriculum, potentially attracting more students to the department. To be eligible for an Option, the student must fill out and present a Student Petition for Option Program in Chemical Engineering to the faculty “champion” for the desired area. The champion is a faculty member with expertise in the area of the Option. Additionally an Option must contain at least 21 credits. Three Options

<table>
<thead>
<tr>
<th>Table 1 Nanotechnology Processes Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class #</td>
</tr>
<tr>
<td>ENGR 221</td>
</tr>
<tr>
<td>ChE 214</td>
</tr>
<tr>
<td>ChE 416</td>
</tr>
<tr>
<td>ChE 417</td>
</tr>
<tr>
<td>ChE 444</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>

| Figure 1. Percentage of 2008-2009 graduating seniors enrolled in each of the four ChE Options at OSU. |
have been available at OSU: 1) Biochemical Processes; 2) Environmental Processes; and 3) Microelectronics Processes and Materials Science. These areas correspond to strengths in the OSU ChE program. A fourth Option, the Nanotechnology Processes Option, has recently been developed. An outline of the curricular requirements is listed in Table 1. It contains six courses—five required courses and an elective—and includes two sophomore-level courses. Four of the five required classes are laboratory-based and emphasize hands-on experiential learning.

The Science, Engineering, and Social Impact of Nanotechnology (ENGR 221) is a general engineering survey course that provides students from Chemical, Biological, Electrical, Environmental, Industrial, Manufacturing, and Mechanical Engineering exposure to the field of nanotechnology; therefore, there is inherently a multidisciplinary approach. On the other hand, Material and Energy Balances in Nanotechnology (ChE 214) is a ChE-specific laboratory-based course, emphasizing how the fundamental skills students have learned in material and energy balances couple to nanotechnology. For ChE students, the approach is to provide students both a breadth of multidisciplinary experiences and a depth of specific technical applications within the discipline. Thus, they are exposed to these complementary experiences early in their undergraduate studies. These sophomore-level courses lead into three upper-division courses already in place. This duality (Breadth plus Depth Pedagogy) is reinforced in senior laboratory (ChE 416), through which students synthesize both aspects in their capstone project, and potentially through their Honors College thesis.

The Nanotechnology Processes Option was approved at the university level in Fall 2006. Since two of the required courses are at the sophomore level, the first graduates became available three years later, at the end of the 2008-09 academic year.

Figure 1 shows the distribution of senior students enrolled in the four Options available in the ChE Program for 2008-09. Of the 55 seniors in Chemical Engineering, 34 have chosen to pursue an Option. The Nanotechnology Processes Option has the most students subscribed, representing 16 students or 29% of the total ChE seniors.

ENGR 221—THE SCIENCE, ENGINEERING, AND SOCIAL IMPACT OF NANOTECHNOLOGY

The Science, Engineering, and Social Impact of Nanotechnology, ENGR 221, is a general engineering survey course with the objective of ensuring all engineering students have access to a course offering basic understanding of the engineering field of nanotechnology. The course learning objectives are presented in Figure 2. The concepts of nanotechnology have been divided into one- to two-week sections, and include applications, properties on the nanoscale, processing, characterization, ethics, and health and safety. The course includes several features intended to promote active learning, including hands-on activities and demonstrations and a final ethics project where students complete a risk assessment of the impact of nanotechnology on society. In addition to introducing technical knowledge surrounding the field of nanotechnology, a goal of this course is to prompt students to synthesize some of the fundamental concepts in science and engineering that they have been taught within the context of nanotechnology.

In the two-hour recitation each week, hands-on activities are completed. Two such hands-on activities are described below. For the section on nanoscale characterization, a scanning electron microscopy (SEM) activity was developed. During this activity, students use a FEI Phenom SEM simulator software program in a virtual laboratory to view a variety of SEM samples, from mosquitoes to a crystal of salt. A screenshot of this simulation and a picture of students performing this

After successful completion of this course, students become able to:

1. Define nanotechnology.
2. Discuss how nanotechnology may impact society.
3. Identify products based on nanostructured materials.
4. Explain how the properties of nanostructured materials differ from their non-nanostructured (conventional) material counterparts.
5. Explain how these unique properties may adversely impact human health and the environment; define the concerns with nanotoxicity research and summarize the status in this area.
6. Explain the difference in approach of top-down and bottom-up manufacturing methods.
7. Describe major manufacturing methods used to produce nanostructured materials and devices and discuss issues in this area.
8. Identify some common methods used for nanomaterials characterization; describe the principles by which each method works and the type of information obtained.
9. Compare two prevalent ethical theories, utilitarianism and absolutism.
10. Perform a risk assessment to determine the best direction for nanotechnology development.

Figure 2. Course Learning Objectives for ENGR 221.
activity are shown on the right side in Figure 3. The simulation allows students to become familiar with the measurement technique and the software. It is followed by a hands-on activity, shown on the left in Figure 3, where students in the class prepare actual SEM samples of their hair, examine these samples using a FEI Phenom benchtop SEM, and analyze the results. This analysis is related back to a “scale of things” activity they completed earlier in the term.

A second laboratory, making ferrofluids,[7] was delivered to integrate two learning outcomes: properties of nanostructured materials and nanomaterials processing. The context of this laboratory follows. Midway through the class, the topic of magnetic fluids is introduced. Two lecture hours are spent discussing the properties of magnetic materials and, specifically, ferrofluids. Topics covered in lecture include: electron configurations of iron and their magnetic effect, crystal structure of several iron oxides, forces on a particle in suspension, reasons only particles on the nanoscale can be used to create ferrofluids, and the relation of the lifetime of the magnetic moment to temperature and volume of the particle. The week after this lecture material is presented, students engage in a hands-on laboratory in which a ferromagnetic fluid is used to allow students to observe the unique properties that are found at the nanoscale. The objective of the laboratory is to reinforce learning on the subjects discussed in lecture the week before. This activity involves the preparation of nanocrystalline-mixed valence iron oxide followed by the addition of an ionic surfactant to create a ferrofluid. Concepts reinforced by this exercise include the importance of understanding the structure of matter (the difference between Fe₃O₄ and Fe₂O₃) and the importance of correct stoichiometry in materials synthesis.

From physics[8] to chemical engineering,[9] active learning practices in the classroom, such as the use of ConceptTests, have been proven to effectively increase student learning. By having students vote by “a show of hands,” this method has been reported to be effective in student learning of nanotechnology.[10] In an effort to promote such active learning in students and to provide opportunities for formative assessment, we have employed a technology-enabled learning tool. The Web-based Interactive Science and Engineering (WISE) learning tool was developed at OSU to use the College of Engineering’s Wireless Laptop Initiative, which requires all undergraduate engineering students to own a wireless laptop. The WISE learning tool allows an instructor to pose to the class questions that probe for conceptual understanding and supports a variety of student response types.[11] After the students have submitted their response, the instructor can review a summary of the results with the class. This tool allows for peer instruction,[12] classroom instruction,[13] or a combination of such active learning practices. For example, a screenshot from WISE of a ConceptTest is shown in Figure 4. This screenshot shows the results that were displayed to the class after individual responses were submitted. The question explores the relationship between a materials property (temperature) of a solid and its surface-area-to-volume ratio. The concept of the size-dependent properties based on surface-to-volume ratios is central to the understanding of nanotechnology, but difficult for many students.[14] Students were asked to select among four possible multiple choices and explain their choice in a short-answer follow-up. The instructor then selected sample responses and displayed them to the class. The results to the multiple-choice questions are shown by the bar graph in Figure 4 and the short answers for three selected cases are displayed below. One of these responses shows a sound understanding of surface-to-volume ratio and its relationship to temperature change. Based on this response, the students divided into peer groups and discussed their answers. When the question was asked again, 21 students answered correctly, although not always with an explanation that clearly demonstrated understanding. The improvement of this type of active learning exercise (32% to 75%) is consistent with that reported in the physics literature.[8]
ENGR 221 was delivered for the first time in Winter 2007 with an enrollment of 31, and again in Winter 2008 with an enrollment of 45. The course was assessed in terms of the achievement of the learning objectives and the effectiveness of the different modes of delivery used during the course. Assessment methods for this course primarily relied on pre- and post-assessments of one kind or another. Overall course pre- and post-concept inventory assessments were administered, in addition to pre- and post-worksheets for two class activities. The other major methods of assessment of student learning were an end-of-term survey and an analysis of critical thinking of the final ethics paper. One of the interesting results is from analysis of an end-of-term survey that asked students to discuss in more detail one concept from their previous coursework that they applied, and how it related to nanotechnology. These responses were then coded according to Shavelson’s cognitive model, which defines achievement in science as consisting of four types of knowledge: declarative knowledge ("knowing that"), procedural knowledge ("knowing how"), schematic knowledge ("knowing why"), and strategic knowledge ("knowing when, where, and how our knowledge applies").[15] Declarative knowledge includes facts and definitions. Procedural knowledge refers to knowledge of the sequences of steps that can be executed to complete a task, whether in the laboratory or to solve a problem. Schematic knowledge includes principles, schemas, and mental models that explain the physical world. Of the 32 responses, 21 were classified as containing elements of schematic knowledge. Students showed a conceptual understanding of the material they discussed; they were able to take concepts introduced in other classes, build on them in the context of nanotechnology, and develop that knowledge into a strong, conceptual understanding of both the basic material and its relation to nanotechnology. Schematic learning is valuable due to its transferability. The high percentage of students displaying this type of learning indicates achievement towards one of the course goals—having students synthesize fundamental concepts in science and engineering within the context of nanotechnology. The detailed assessment is presented elsewhere.[16]

It is believed that the pedagogical features discussed above play a significant role in the success at promoting the student’s use of schematic knowledge, even at the sophomore level. This approach is consistent with the successes of scientific teaching in biology.[17] These methods encourage students to construct new knowledge and develop scientific ways of thinking, and they provide students and instructors feedback about learning. While the discussion above illustrates these pedagogical features in the context of nanotechnology, this approach can be applied to any course in the chemical engineering curriculum.

**CHE 214—MATERIAL AND ENERGY BALANCES IN NANOTECHNOLOGY**

Material and Energy Balances in Nanotechnology, ChE 214, is a chemical engineering laboratory course intended to give students an immediate way to apply what they learned in Material and Energy Balances (the first strongly technical chemical engineering courses students take) in the context of a hands-on nanotechnology laboratory. The course learning objectives are presented in Figure 5. Comparison of these learning objectives with those of ENGR 221 (Figure 2) reveals their complementary intent of depth and breadth. For most

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**Figure 4. Screenshot from the Web-based science and engineering (WISE) learning tool.**

After successful completion of this course, students become able to:

1. Quantitatively describe the rate of reaction through real-time measurements of changes in the mass of product carbon nanotubes.
2. Calculate molar and mass concentrations based on flow rates of mixture-gas components and correlate them to GC based concentrations.
3. Calculate the fractional conversion of limiting reactant based on the reactant inlet and outlet flow rates.
4. Calculate product yields based on the gas-flow rates and correlate them to mass-based product yields.
5. Use temperature measurements at the reactor inlet and outlet to explain heats of reaction in conjunction with endothermic and exothermic reaction concept.
6. Predict reactor outlet temperature and compare it to actual temperature measurements.
students, this course will directly follow ENGR 221, and they will already have completed a survey course in nanotechnology. ChE 214 is a laboratory course, consisting of a two-hour lecture period and a four-hour laboratory period each week. Each laboratory is not an isolated occurrence, but instead builds on the previous laboratories. For example, the catalyst the students prepare in the first laboratory is used throughout the course to grow nanotubes. The lecture periods consist of one hour of new material followed by an hour-long quiz. Students are given weekly homework assignments intended to prepare them for laboratory.

In this course students grow carbon nanotubes from ethylene in three different reactors: a thermo gravimetric analyzer (TGA), a vertical packed-bed reactor, and a plasma reactor. The TGA is used to make real-time measurements of the growth rate of carbon nanotubes by measuring the change in mass with time. Based on a group’s choice, either the temperature dependence or the concentration dependence of the growth rate have been studied. The vertical packed-bed reactor, shown in Figure 6, is used for batch-wise synthesis of carbon nanotubes in large quantities using the reaction conditions of the group’s choice, as determined by the TGA experiment. Figure 6 also shows a photograph of the nanotubes one of the groups grew, and an SEM that they took of their product. Finally, in one of the laboratory sessions, students use a plasma reactor to grow carbon nanotubes. This experience allows them to contrast a system for high-volume manufacture of bulk nanotubes and a system for high-value manufacture for nanoelectronics applications.

The students are required to predict the amounts of product nanotubes based on the rate data obtained with the TGA as well as the changes in the gas compositions and flow rates between the reactor inlet and outlet streams. They should then discuss any differences between the predictions and the actual product mass. They are also required to predict increases in temperature based on an adiabatic reaction assumption, compare their predictions with the measured increases in temperature between the inlet and outlet gas streams, and discuss possible causes for the deviations between the theoretical predictions and actual measurements. In these ways, they are prompted to reconcile their experimental results with their conceptual understanding of material and energy balances that they have learned earlier in the year. The intent is to promote an integrated construction of knowledge in students of both chemical engineering fundamentals and nanotechnology.

As a course specific to chemical engineering, ChE 214 has been exclusively taken by chemical engineering majors. There were 14 students who completed the course in Spring 2007 and 12 in Spring 2008. The demographics changed considerably in the two years the course was offered. In 2007, there were 13 sophomore students and one senior while in 2008 there were six sophomore students and six seniors. Again, the course was assessed in terms of the achievement of the learning objectives.[1] Since the course consisted primarily of laboratory sessions, observations and survey of these sessions were the primary tools of assessment. In addition, pre- and post-tests were administered, along with an end-of-term survey and analysis of the final project reports (which covered most material introduced in the course). The survey was intended to reveal the students’ perception of what they were expected to learn and the concepts they employed in each laboratory. Again, the responses to each question of each survey were categorized in terms of declarative, procedural, or schematic knowledge. The first conclusion from this analysis is that seniors are better able to think about the laboratory material schematically than sophomores. A second conclusion is that students are more able to respond schematically when asked directly about a concept than they are when asked about what they were intended to learn in the laboratory. In fact, when asked about what they learned in laboratory, students are much more likely to demonstrate procedural knowledge and describe the physical system and its operation rather than the concepts behind why the system behaves as it does. This result is especially true for sophomore students.

**NANOTECHNOLOGY-BASED CAPSTONE LABORATORY PROJECTS**

Students who select the Nanotechnology Processes Option are required to do a nanotechnology-based capstone project as the major project in Chemical Engineering Lab II and
III (ChE 415 and 416). The deliverables for the 15-week capstone project include participation in a poster session at OSU’s “Engineering Week,” where graduating seniors from all departments in the College of Engineering display their senior project work, an oral presentation at an internal mini-symposium organized specifically for the purpose, and a final technical written report. In addition to the projects, the instructors offer a short subset of the lectures focused on a very brief survey of nanotechnology at a level appropriate for seniors, to ensure that those students that have not elected to work on a nanotechnology-related project have a general understanding of nanotechnology.

While the first batch of students in Nanotechnology Processes Option did not reach the senior level until 2008-2009, two laboratory projects were conducted by students in 2005-2006 and three projects were conducted by students in 2006-2007. Five student groups have completed nanotechnology-based senior projects in 2008-2009. These projects have been constructed to be of a broad enough scope so that those students who were capable would be encouraged to apply schematic and strategic knowledge of chemical engineering science while others who engaged more consistently using procedural knowledge could still complete a meaningful project. The 10 projects that have been conducted to date are listed in Table 2.

### STUDENT SURVEY

After completing the sophomore-level nanotechnology course or courses, students were given a survey with two parts. In the first part, they were asked to rate the extent to which the courses assisted them to make connections to content from other courses, pursue a career in nanotechnology, and increase their interest in nanotechnology. Students rated these aspects on a Likert scale of 1-5, with 1 as a strongly disagree and 5 as a strongly agree. The average results are shown in Table 3. The second part of the survey asked students to rate the effectiveness of the courses in improving their ability to perform several categories of tasks, on a Likert scale of 1-5 (as in the previous question). The average results for each task are shown in Table 4.

The students believed that the sophomore-level content was useful toward pursuing a career (4.37), but did not believe the courses increased their interest (3.03); perhaps because those students who selected these courses already had an interest. They moderately agreed that the content helped them make connections to other courses (3.63); however, many more students took only ENGR 221 than took both courses. The perception of an increase in skills and abilities by the sophomore-level course(s) was rated high, with students feeling strongly that they could work successfully on a team (4.68), demonstrate understanding and application of principles in nanotechnology (4.58), and identify the nature of a design problem (4.53).

<table>
<thead>
<tr>
<th>Project Title</th>
<th>Description</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production of Aligned Carbon Nanotubes</strong></td>
<td>The assembly of a reactor for the production of aligned films of carbon nanotubes using ethylene pyrolysis on iron catalysts and growth of carbon nanotubes by ethylene pyrolysis.</td>
<td>2005-2006</td>
</tr>
<tr>
<td><strong>Nanocrystalline Photovoltaic Devices</strong></td>
<td>Preparation of photovoltaic devices by spin coating nanocrystalline precursors onto polymeric substrates.</td>
<td>2005-2006</td>
</tr>
<tr>
<td><strong>Production of Aligned Carbon Nanotubes</strong></td>
<td>The assembly, testing, and operation of a system designed to produce films of aligned carbon nanotubes on a surface using pyrolysis of ethanol on molybdenum acetate (Mo₂O₃Ac₂) based catalysts.</td>
<td>2006-2007</td>
</tr>
<tr>
<td><strong>Nanostructured Polymers</strong></td>
<td>The use of diatom skeletons as masks to plasma-etch nanostructured designs onto polymeric surfaces.</td>
<td>2006-2007</td>
</tr>
<tr>
<td><strong>Magnetic Nanocomposites</strong></td>
<td>The production of Fe₃O₄ magnetic nanocomposites by sol-gel processing of Fe(acac)₃ precursors.</td>
<td>2006-2007</td>
</tr>
<tr>
<td><strong>Exploration of Low-Cost Implementation of Reactive Systems in Microreactors</strong></td>
<td>Development of low-cost, inkjet-based contact lithography and wet etching of glass to produce a microchannel-based reactor and demonstration with alkaline hydrolysis of ethyl acetate solutions in water.</td>
<td>2008-2009</td>
</tr>
<tr>
<td><strong>Microreactor-Enhanced Redox Flow Cell Battery</strong></td>
<td>Construction of a redox flow cell zinc-bromine secondary battery suitable for energy storage research and demonstrations.</td>
<td>2008-2009</td>
</tr>
<tr>
<td><strong>Sputtering Metal Films for Microelectronics: Forming Barrier Layers Using CuX Targets</strong></td>
<td>Demonstration and characterization of self-formation barrier technology using sputtered CuMn blanket films followed by thermal anneal.</td>
<td>2008-2009</td>
</tr>
<tr>
<td><strong>Nanobiosensors</strong></td>
<td>Protein-sensitive field effect transistors manufactured commercially available silicon-on-insulator wafers. The final devices are high performance (specific detection below 100 fM) and are commercially exciting.</td>
<td>2008-2009</td>
</tr>
<tr>
<td><strong>Synthesis of Doped Titanium Dioxide Nanoparticles</strong></td>
<td>Synthesis of TiO₂ nanoparticles that are doped with an indicator element that is detectable by ICP-AES. The objective of this work is to demonstrate proof-of-concept for further work involving use of more expensive lanthanides as dopants. Ultimately, the doped nanoparticles will be used in experiments examining the fate and transport of nanomaterials in the environment.</td>
<td>2008-2009</td>
</tr>
</tbody>
</table>
CONCLUSION

The implementation and assessment of the Nanotechnology Processes Option in Chemical Engineering at Oregon State University has been described. Its foundation builds upon two newly developed sophomore-level courses: a general engineering survey course that exposes students to the scientific basis, potential technological and societal implications of nanotechnology, and a ChE-specific laboratory-based course that integrates the fundamental knowledge students have learned in Material and Energy Balances with Nanotechnology. The approach is to provide students with both a breadth of multidisciplinary experiences and a depth of specific technical applications within the discipline early in their undergraduate studies. In addition, nanotechnology-based capstone projects have been integrated into the senior laboratory class, with 10 different student teams participating to date. Nanotechnology-related content has also been added to two senior-level courses that are part of the Option.

The Option described contains a coherent set of courses that have been constructed to elicit high cognitive levels in students beginning early in the curriculum. Initial assessment of this approach is positive. Effort will be required, however, to keep the content up-to-date as the technology rapidly evolves. Additionally, the sophomore-based laboratory course has a large overhead per student served, requiring both institutional support and instructor dedication to continue.

ACKNOWLEDGMENTS

The authors are grateful for support provided by the Intel Faculty Fellowship Program and the National Science Foundation’s Nanotechnology Undergraduate Education Program, under grant NUE–0532584. We gratefully acknowledge the generous donation of a Phenom.ED benchtop scanning electron microscope by the FEI corporation through their beta test program. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES


TABLE 3

<table>
<thead>
<tr>
<th>Statement</th>
<th>Average Rating</th>
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</thead>
<tbody>
<tr>
<td>The content helped me make connections to what I learned in other courses.</td>
<td>3.61</td>
</tr>
<tr>
<td>The content will help me in pursuing a career in nanotechnology.</td>
<td>4.37</td>
</tr>
<tr>
<td>The courses have increased my interest in nanotechnology.</td>
<td>3.03</td>
</tr>
</tbody>
</table>

TABLE 4

<table>
<thead>
<tr>
<th>Task</th>
<th>Average Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify the nature of a design problem or challenge related to nanotechnology</td>
<td>4.53</td>
</tr>
<tr>
<td>Demonstrate my understanding and application of principles in nanotechnology</td>
<td>4.58</td>
</tr>
<tr>
<td>Communicate the principles of nanotechnology in speech and writing to a wide audience of peers and experts</td>
<td>4.13</td>
</tr>
<tr>
<td>Work with a team to successfully complete large scale projects</td>
<td>4.68</td>
</tr>
</tbody>
</table>
IN SEARCH OF THE ACTIVE SITE
OF pMMO ENZYME:
Partnership Between a K-12 Teacher, a Graduate K-12 Teaching Fellow, and a Research Mentor

KATHERINE K. BEARDEN, DANIELA S. MAINARDI
Louisiana Tech University • Ruston, LA
TANYA CULLIGAN
Caddo Parish Magnet High School • Shreveport, LA

There are many sources available for the implementation of outreach at Louisiana Tech University (LA Tech) and in the surrounding community. Within the College of Engineering and Science, Louisiana Tech has two National Science Foundation (NSF)-funded programs: the GK-12 Creating Connections (NSF grant 0638730) program, and the Nanoscience Education and Research Outreach (NERO) program’s Research Experience for Teachers (RET) (NSF grant 0602029). These programs create an environment for graduate students, university faculty, and teachers in the surrounding community to 1) develop inquiry-based science laboratories for K-12 grades; 2) expose K-12 teachers to nanotechnology principles, equipment, and research; and 3) engage K-12 teachers in specific research experiences spanning six weeks in summer in which they are mentored by university faculty. Hence, in this paper we show how education programs at a university can integrate and use available resources to improve established individual programs.

Through the implementation of the NERO RET program at LA Tech since 2007, 16 local teachers have participated in a 6-week summer program; which contains professional development and research components. The RET program provides the unique opportunity for collaboration between a K-12 teacher (NanoResearcher), a GK-12 graduate student (Teaching Fellow) and a Louisiana Tech faculty member (Research Mentor) in science, technology, engineering, and math disciplines (STEM).
There are many RET programs across the United States that offer a variety of benefits. Although each program is different, teachers of the middle school, high school, and community college levels have participated and paired with university faculty to conduct a specific project. All RET programs allow teachers to experience scientific research firsthand, but each program is designed around the strengths of the participating university and incorporates different professional development tools. Possible topical areas of research include optics, materials science, and nanotechnology.

Tanya Culligan (NanoResearcher), a tenth-grade Biology I and twelfth-grade Biology II AP teacher at Caddo Parish Magnet high school in Shreveport, Louisiana, has participated in the 2007 and 2008 NERO RET programs at LA Tech. In both opportunities, she paired with Daniela S. Mainardi (Research Mentor), an assistant professor of chemical engineering and nanosystems engineering at Louisiana Tech, and Katherine K. Bearden (Teaching Fellow), a doctoral student in chemical engineering under Mainardi’s supervision.

Uniquely, the program at Louisiana Tech University has been designed for the collaboration of the three participants, offering an opportunity for K-12 pedagogy to be communicated (to Bearden), reinforced (by Culligan), and enhanced (by Mainardi). Bearden is first introduced to pedagogical techniques through the GK-12 orientation. During this two-week session the 5- E Learning Cycle, Bloom’s Taxonomy, and techniques to translate research into the classrooms are covered. This cyclical expression of ideas and skills increases the knowledge and implantation in the K-12 classrooms. Through this design we demonstrate how programs at a university can integrate and use available resources to improve established individual programs. We believe that this is an important value that can be beneficial for the educator audience.

The novelty of this particular RET program is that it is directly linked to Louisiana Tech’s GK-12 program. Bearden is also a full-time participant in the NSF GK-12 program. Her position as a Teaching Fellow requires her to have 10 contact hours with K-12 students each week. Bearden benefited by having a teacher (Culligan) to serve as a reference and collaborator while creating research-based activities to disseminate to students participating in the K-12 program. Hence, the unique grouping of Culligan, Bearden, and Mainardi for research initiatives has been reached broadly across the K-12 community in Northern Louisiana.

Particularly, the objectives of the Louisiana Tech NERO program are to: 1) engage middle and high school teachers (NanoResearchers) and their students in bio/nanotechnology research through summer research experiences; 2) guide teachers as they develop materials to translate their understanding of the research process into classroom learning experiences; 3) build lasting relationships among teachers, researchers, K-12 students, and graduate students; 4) communicate the scientific research process to teachers, students, and the community; and 5) increase interest of K-12 students in pursuing STEM careers.

PROGRAM OVERVIEW AND RESEARCH SETTING

Throughout the program, RET participants are first introduced to concepts of nano-scale science and engineering in the course of a series of seminars focusing on scientific literacy. They are engaged in hands-on experiences that aid them in understanding protocols, running simple experiments, collecting data, and analyzing the corresponding results. Combined with professional development activities, RET participants are exposed to independent research work under a STEM faculty member with guidance from a Teaching Fellow. Research projects available for the RET participants focus on various branches of nano-scale science, such as the fabrication of cellular capsules for regenerative medicine, analysis of varying L-arginine concentrations on platelet adhesion, and modeling of enzyme docking for environmental applications.

At the end of the 6-week program, the RET participants orally present their independent research work, as well as education activities they have designed together with their research mentors on how to take back to their classroom the research concepts they have learned. Explaining nano-scale research to students in the K-12 grade levels is truly challenging; however, exposure to concepts of nano-scale science creates a foundation for student inquiry and provides students with extensive applications of the abstract science concepts they learn within their curriculum.

The research performed by the Mainardi research group uses molecular modeling techniques to study chemical and biological systems at the nanoscale. Computer simulations allow researchers to view atomic interaction that may not be visible (by microscopic techniques) during a reaction. The same information-surround modeling techniques (such as mathematical basis and appropriate usage) are incorporated into a course, Nanosystems Modeling, created and taught by Mainardi. The course is offered to undergraduates and graduates students in the College of Engineering at Louisiana Tech University. The usage of modeling techniques can visually demonstrate to students what is only covered conceptually in many science classes. The pedagogical influence of Bearden and other members of the Mainardi research group accelerated Culligan’s understanding and use of the program.

RESEARCH BACKGROUND, METHODS, AND RESULTS

In 2008, Culligan worked during her RET summer experience in the Mainardi computer laboratory on the modeling of enzymes docking with potential environmental technology applications involving methane (natural gas; chemical formula \( \text{CH}_4 \)) bioremediation. Methane is well known to be a pol-

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lutant and about one-third of its atmospheric concentration is produced by wetlands and lakes.\[^{[7]}\]

Methane conversion to methanol by Methanotrophic bacteria, which are found in rice fields, is considered as an important sink for CH\(_4\).\[^{[8,9]}\] Particularly, the role of methanotrophs\[^{[10]}\] in the reduction of global emissions of methane, their potential commercial use for the biotransformation of numerous organic chemicals into valuable products, and their capacity for the bioremediation of toxic pollutants have been well recognized\[^{[11,12]}\].

Particulate Methane Monooxygenase (pMMO) and Methanol Dehydrogenase (MDH) enzymes are found in Methanotrophic bacteria. While pMMO is known to exhibit the unique catalytic capacity for converting methane to methanol\[^{[10]}\] under ambient conditions using dioxygen as the oxidant,\[^{[13]}\] MDH is well known to catalyze the oxidation of methanol to formaldehyde, which is assimilated into biomass or involved in some other processes (Figure 1).\[^{[14,15]}\] During these processes, electrons are produced and can be further collected as electricity.

Even though Lieberman, et al., suggested that the active center (site) of pMMO may contain two copper ions and several amino acids, this topic is still controversial.\[^{[16]}\] Moreover, how methane is converted to methanol by pMMO is completely uncertain. On the other hand, the crystal structure of MDH has been unequivocally determined and its active center fully characterized to contain a Ca\(^{2+}\) ion, a pyrroloquinoline quinine (PQQ) molecule,\[^{[17-20]}\] 13 amino acids, and several water molecules. Thus, what is not understood is 1) how the two enzymes (pMMO and MDH) work together in the bacteria and 2) the specific location of the active site of pMMO—and that was the topic explored by Culligan during her 2008 summer experience in the Mainardi group at Louisiana Tech.

Since MDH and pMMO are found together in the same bacterium, Culligan (NanoResearcher) was assigned the investigation of different docking situations for these enzymes. Hence, Culligan’s overall goal was to determine the most likely configuration of the two enzymes to gain insight into the actual location of the pMMO enzyme’s active site, based on the hypothesis that the two enzymes’ active centers are closely located with respect to each other. To achieve her goal, Culligan needed to 1) create appropriately sized models of the MDH and pMMO enzymes for computation purposes, 2) optimize the geometries of the enzymes individually, and 3) explore different MDH/pMMO arrangements by performing geometry optimizations to find the lowest energy configuration leading to the most likely position for the interacting enzymes (as they would within the Methanotrophic bacteria were they are found).

A two-day mini-orientation was conducted first to familiarize Culligan with the software used in the research. A series of tutorials was guided by Mainardi, Bearden, and other members of the Mainardi research group, and a short-cut reference document was supplied to Culligan. The mathematical basis of the research was explained and the implementation of the project was completely defined right before Culligan started her research work.

The computational modeling technique used to obtain results for Culligan’s simulations is Molecular Mechanics.\[^{[21]}\] The principle behind Molecular Mechanics is that it uses an energy equation to describe bonded inter-atomic interactions including bond lengths, angles, and torsion, and also nonbonded interactions such as electrostatic or Coulomb interactions. Such an equation is known as a Force Field,\[^{[21]}\] and during the Molecular Mechanics simulation, this function is minimized to find an equilibrium structure of the molecular system, which represents a stable conformation. All of these concepts are presented to Culligan using prepared PowerPoint presentations and activities that were created by Mainardi for the course Nanosystems Modeling, which is available as an elective to undergraduate and graduate students in engineering curricula. Thus, by using the module Forcite of the Materials Studio software by Accelrys, Inc.,\[^{[22]}\] for those simulations, the lowest energy configurations for the MDH/pMMO model system were found and fully structural characterization performed.

Culligan first built a model for the MDH enzyme based on the current state of knowledge on the location of its active site. The MDH enzyme, entry 1H41 of the Protein Data Bank, was imported and its active site was found and highlighted. Then, Culligan added an amino acid shell surrounding the entire MDH active site thus creating a 1,300 atom model to represent MDH (Figure 2a). The MDH model was then geometry minimized using Molecular Mechanics.

A second model, for the pMMO enzyme, was created based on the current state of knowledge on its active site location and contents using the entry 1YEW of the Protein Data Bank.

![Figure 1. Methane conversion to methanol (by pMMO enzyme) and to formaldehyde (by MDH enzyme) by the same organism (Methanotrophic bacterium).](image-url)
The active site of pMMO is not fully understood and is still being explored; however, current research seems to indicate that it is part of a complex involving four ions and some amino acids. The pMMO model was then geometry minimized using Molecular Mechanics (Figure 2b).

Once the optimizations of the models were complete, they were paired together in 10 different configurations to determine a likely position for the interaction (docking) of these two enzymes within the Methanotrophic bacteria. All cases were geometry minimized using Molecular Mechanics simulations and the most stable conformation was identified (Figure 2c).

After completing each simulation, Culligan recorded relevant bond lengths and angles between atoms of particular interest. The information gathered provides a baseline of investigation and indicates a region of particular interest to concentrate on in future simulations in the Mainardi research group. Thus, this information aids the ongoing investigation by Bearden (Teaching Fellow) to determine if the two enzymes can have close contact to facilitate the methane-to-methanol oxidation reactions. In trying to orient MDH and pMMO in search of the configuration most likely used in nature, the complementary shapes of the enzymes suggest that they do interact and their active sites are not too far apart to make oxidation of methane to methanol in pMMO and methanol to formaldehyde in MDH a concurrent and regulatory process. Further simulations are needed to establish a trend in determining the most stable configuration of the MDH/pMMO interaction.

CREATION OF TRANSLATIONAL RESEARCH MODULES AND COLLABORATION BENEFITS

As part of the RET initiative, participants had education goals along with their research goals. Culligan’s education goal was to design and prepare learning materials and “in vivo” demonstrations of integrated research and educational activities for the students in her class. Culligan also collaborated with Bearden and Mainardi to create a learning module to take back to her biology classes. This component of the program, although simple in statement, proved challenging. The important themes in the research were first identified (i.e., molecular modeling, bioremediation, enzymes, catalysts, enzymatic reactions, among others). Secondly, the themes’ concepts were explored and examined to find ideas that could be applied to the specific courses taught by Culligan (i.e., hydrogen bonding within the DNA structure). This technique was applied a second time when Bearden created two translational activities to present to middle school students as part of her involvement in the GK-12 program at Louisiana Tech.

As a tenth-grade Biology I and twelfth-grade Biology II teacher, Culligan recognized that students usually have difficulty visualizing matter due to its unobservable basis, and discussed her concern with Bearden and Mainardi during her RET experiences in summer 2007 and 2008. Mainardi explained to Culligan that using molecular modeling in the classroom would provide the basis for individual learning, and the possibility to “visualize” abstract concepts through computer simulations and graphics, permitting representations and demonstrations of models of the micro and nano world. The effect of computer animations on college student mental models of chemical phenomena has been extensively studied and tested, and results have shown that the animations helped students understand the subject matter better while improving their ability to construct dynamic mental models of chemical processes.

The choice of model type, which is a challenge for a teacher, has an impact on the image students create concerning the ways in which molecules are shaped and how they function in the “real” world from a scientific viewpoint. Computerized molecular modeling also has been successfully used as a tool to improve chemistry teaching classes of tenth graders, and this was the motivation for Culligan, Bearden, and Mainardi in Summer 2008 for creating an education module to incorporate modeling and molecular building in classroom activities to help students understand concepts in molecular geometry and
bonding while having an enjoyable learning process.

To communicate the fundamentals of molecular systems, molecular simulations have been proven to be excellent tools, and the possibility of using freely available software to visualize molecular shapes and build simplified models of molecular systems motivated Culligan to promote interest and guide inquiry among her students.

Hence, from her learning module, Culligan took molecular modeling into her classroom and allowed her students to build molecular groups (atom by atom) including amines, ester, and hydroxyl groups using available software. She used the visualization aspects of the modeling software to present the concepts of condensation, hydrolysis, and nitrogen base bonding. The students also used ball-and-stick components from a purchased chemistry kit to physically build the purines (adenine and thymine) and pyrimidines (cytosine and guanine) structures found in DNA. This activity was constructed to confirm that adenine and thymine have two hydrogen bonds and cytosine and guanine have three hydrogen bonds, a benchmark in the Louisiana biology curriculum.

A second learning module Culligan created used molecular modeling to depict the different processes involved in cellular respiration. Students were engaged in the building of the molecular groups involved in the different steps of respiration (i.e., glycolysis, pyruvic acid breakdown, citric acid—or Krebs—cycle, and the electron transport chain). Students used the visualization aspects of the modeling software to present the concepts of hydrogen ions transporting and the use of an electron transport chain. The students were assessed in a carousel activity incorporating the information retrieved from the molecular bonding interactions, through computation and ball-and-stick models.

Informal student interviews were conducted and indicated an increase in the student enthusiasm with marked statements as "Can we use the computers again?" Many students even purchased their own ball-and-stick kits to practice at home. The incorporation of these visual and tactile components increases the students' understanding of atomic-level interactions. From the exposure to ball-and-stick kits and incorporation of the computer simulations, students' understanding increased by a documented 10% improvement on content test scores compared to the previous year. The same topics were taught each year and the identical test from the previous year was not released to students.

As part of her involvement in the GK-12 program, Bearden was requested to create two translational research presentations to convey 1) the importance of modeling and 2) the topic of her research and the necessity of computers in her research. She first gave these presentations as one unit to the RET participants. Based on their feedback and through the individual guidance of Culligan, these activities were developed into full lessons that were delivered at her K-12 partner schools and at two requested guest presentations. Links to the presentations and pictures of the lesson delivery 1) “All Eyes on Atoms” and 2) “What Makes a Beautiful Model?” can be found at <http://www2.latech.edu/~klk021>.

Although Bearden receives most of her research topic guidance from Mainardi, she increased her understanding of the research project by explaining it to Culligan and continuing to serve as a mentor to Culligan during the summer months. Culligan in turn aided Bearden in furthering her position as a Teaching Fellow by helping Bearden develop pedagogy skills and make the appropriate connections in translating the research into modules and activities for Bearden’s student base. As a Teaching Fellow, Bearden’s teamwork, communication, and research skills were enhanced by the experience. This is something often found when graduate students participate in K-12 outreach that improves their future collegiate teaching. Each key participant came away from the program with distinct benefits.

Benefits to Mainardi: 1) Culligan was an additional researcher to her group; 2) Results obtained by Culligan furthered the research of Bearden (and thus Mainardi); and 3) Culligan and Culligan’s classroom serve as a dissemination outlet for Mainardi’s research.

Benefits to Bearden: 1) increase in scientific communication skills and research skills through the practice of guiding Culligan through research project and analyzing results; 2) Culligan guided Bearden in translating research into learning module for K-12 audience; and 3) increase in teamwork and leadership skills through the unique grouping.

Benefits to Culligan: 1) the learning experience provided by the NERO RET program expanded her knowledge of ongoing research in the nanotechnology field, instilled professional development tools, and created a module to implement in her classroom to convey the concepts of molecular modeling; 2) the partnership gave Culligan better appreciation for the opportunities for collaboration available at the university and K-12 levels of education that provide direct channels for research to be integrated into K-12; and 3) the development of modules with the aid of Mainardi and Bearden enriched her teaching by using computers to convey the concepts involved in molecular modeling and to convey difficult topics in the curriculum.

CONCLUSIONS

This unique grouping allowed for the collaboration to benefit all parties involved. The program outline, research background and results, and education-related products were explained in this paper to describe to readers how a RET project can be expanded to incorporate other parties to increase learning of and exposure to chemical engineering concepts, such as those explored through molecular modeling techniques. During the six weeks of work—a very short
period in the academic research community—Culligan was able to produce a sound baseline for further research. Her results aided in directing Bearden (GK-12 Teaching Fellow) to a region of particular interest in the goal of determining the active site of the pMMO enzyme. As a Teaching Fellow, the experience enhanced Bearden’s teamwork, communication, and research skills.

ACKNOWLEDGMENTS

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We also appreciate the direction and constant assistance provided by Dr. David K. Mills and Linda Ramsey of Louisiana Tech University, principal and co-principal investigators, respectively, together with Mannardi of the NSF NERO-RET and NSF-GK-12 programs, that financially supported Tanya Culligan’s summer experiences and Katherine K. Bearden’s doctoral work.

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2. Montana State University Department of Physics
3. Nanotect at University of California at Santa Barbara
4. University of Wisconsin at Madison Materials Research Science and Engineering Center
One problem when teaching many laboratories is the lack of participation of students in the experiments from beginning to end. Often teaching assistants prepare the necessary solutions and they demonstrate the use of very specialized equipment (or even, in some cases, perform the experiment). This trend has become more acute as the instrumentation used in laboratories has become increasingly expensive. Students' limited participation in the experiments has not precluded us from expecting them to produce meaningful data in spite of their lack of experience. We overemphasize student performance during their basic learning phase. This increases the level of tension in the classroom and leaves little room for error. Both of these problems limit student creativity and the development of problem-solving skills. Approaches such as problem-based learning[1] and experimental design[2] have been explored to alleviate the problem. Unfortunately, it is very difficult to implement such approaches when the students lack basic laboratory skills.

One approach in the teaching of laboratories is to provide the students with a detailed laboratory guide. These guides are often quite comprehensive and leave little room for improvisation. After completing their work, the students write a report following a pre-established template. At the end of the semester, the students move happily into the next set of courses. After graduation, the students must adapt from a highly structured environment to one in which they are not...
spoon-fed anymore. I believe that this constitutes a weakness that needs to be addressed. Poor communication between the basic sciences and our discipline places that burden on us. Moreover, recent trends (partly driven by budget cuts) of replacing wet labs with dry ones or with a dry/wet combination of replacing entire unit operations labs by virtual ones may make matters worse.

Students in the Chemical Engineering Department at the Missouri University of Science and Technology (formerly the University of Missouri-Rolla) take a series of laboratory courses in the Chemistry, Biology, and Chemical Engineering Departments. The Missouri S&T Chemical Engineering curriculum has a Biochemical Engineering Emphasis program in which the unit operations laboratories have been replaced by Biochemical Separations and Bioreactors Laboratories. In addition, the students take several biology courses, including molecular genetics, general biology, and microbiology; at least two of these classes have laboratory sessions. I have been teaching the Bioseparations Laboratory for the last 15 years. It did not take me long to realize that the ability of the average student coming into my class (normally first-semester seniors) to function in a laboratory setting is questionable, to say the least. Most importantly, I have found that most do not know how to “move” in a laboratory.

There is no quantitative measure for use in characterizing the difficulties that the students have functioning in a laboratory setting. Despite this, it is very easy to find a few examples here and there of students unable to function properly in a laboratory. Once, a young student came to see me in distress. There was some fear in her eyes, so I sat down ready to hear some disastrous news. “I needed to use the small centrifuge but when I tried, it did not work properly. The centrifuge was moving very fast along the bench; I was afraid it was going to fall down so I stopped the experiment,” she said. I sighed in relief. Nothing was broken and the students were in one piece. The ease of the stubborn balance happened a few years later. A student was weighing potassium phosphate on a top-loading balance to prepare a buffer. I was in the vicinity when it happened. She was in the vicinity when I heard: “This balance is definitely not working!”

“Uh oh,” I thought, “Here goes my budget for the semester.” As I asked him what the problem was, he showed me how he was adding a lot of material to the weighing dish but the numbers in the digital display did not change. When I noticed that he had not removed the balance cover, I could not help but laugh. More tragic (and costly) are the stories of the “constant pH meter,” which was caused by the smashing of the pH meter electrode against the bottom of a beaker, and of the “broad range micro-pipette,” which occurred when a student tried to measure 1.1 mL with a 100-1000 µL adjustable micro-pipette. These stories are all from my Bioseparations Lab, and they were partly caused by lack of training. Somehow, I feel sympathetic to my chemistry and biology colleagues who do not allow the students to use anything in their laboratories. Of course, their approach does not teach the students anything, but at least their strategy is cheap. Obviously, better approaches are necessary.

OUR APPROACH

We decided a few years back to attempt to alleviate the poor laboratory training of the students by dividing our Bioseparations Laboratory into two parts: Training and Project. During the first weeks of the semester, the students learn the fundamentals of various separations techniques (mainly membrane filtration and chromatography) as well as ancillary techniques (for example, centrifugation, spectroscopy, use of pH and conductivity meters, gel electrophoresis, etc.). This portion of the semester consists of six to eight short experiments (one to two weeks each) in which the students follow recipes and write technical reports in scientific journal format. There is no penalty for failure as long as they have been careful in their work. This training section requires close monitoring of the students. We have found that with the exceptions of Ph.D. or M.S. candidates in the author’s laboratory, teaching assistants are not very useful in our Bioseparations Laboratory. New graduate students in chemical engineering can be trained in a reasonable amount of time to assist the students in a traditional unit operation laboratory. Unfortunately, the same is not true for our Bioseparations class, where the instruments, techniques, and the necessary theoretical background are foreign to traditional chemical engineering graduates. Therefore, many semesters I have taken sole responsibility of teaching the class. The students then pursue a four-week-long project in which they apply the techniques learned during training. Although the number of contact hours is considerable during the training portion of the lab, that is somehow compensated for during the project part in which the students work mostly alone.

TRAINING

A few laboratories that we use for training purposes are included in Table 1. Most of these experiments are described in detail in the work by Forciniti.[15] This list is not exhaustive, as the experiments included in the training section are tailored to the type of projects planned for the second part of the semester. The students need to be trained in general laboratory practices, but at the same time they must prepare themselves for the operations that they will use in a particular project. The only recurrent themes in the laboratories included in Table 1 are chromatography and ultrafiltration because of the indisputable importance of these operations in the bioprocessing sector. I have included in the table the main tasks involved in each laboratory as well as the overall goals of each training section.

A common goal of each training laboratory is to gain general laboratory skills. Table 2 summarizes the basic skills that the students learn in the training laboratories. Notice that we
emphasize repetition of these basic skills. We have found that repetitive direct instructions are necessary for the students to perform properly. The training in the use of each piece of equipment is quite intensive. For example, the students learn the working principles of a pH electrode before they learn how to calibrate and operate a pH meter.

To illustrate, the ultrafiltration experiment is described below. Ultrafiltration is a means of concentrating dilute biological solutions that are heat sensitive. The solution to be concentrated is added to a cell that contains a membrane that prevents large molecules from passing through. The membrane’s pore sizes range from 0.001 to 0.02 µm. Ultrafiltration can also be used to partially separate proteins whose size difference is relatively large.

A common problem with ultrafiltration is concentration polarization, which is a build-up of the solute at the surface of the membrane that reduces the trans-membrane flux.

The learning objectives of this laboratory are: 1) to understand the functioning of a cross-flow ultrafiltration device; 2) to understand the concept of concentration polarization; and 3) to determine the mass transfer coefficient on the retentate side of the membrane (in the pressure-independent regime). The students perform all the experiments in duplicate. They are asked first to collect the necessary materials, which are dextran (MW 150,000 or higher) and NaCl, and to prepare a saline solution (0.050 M NaCl) and dextran solutions at various concentrations in 0.050 M NaCl. The students are then introduced to the instrument. For example, they may be asked to use the Labscale TFF system by Millipore equipped with a cross-filtration membrane modulus with a molecular weight cut off of 100,000. The instructor describes the main components of the instrument, briefly indicates its capabilities, and more importantly, offers the students a copy of the manual and points out the homepage of the manufacturer.

The students identify the pressure-independent regime by doing experiments at various dextran concentrations. The

\[ \text{TABLE 1} \]

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Tasks</th>
<th>Goals</th>
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<tbody>
<tr>
<td>Gel Permeation Chromatography</td>
<td>Buffer Preparation</td>
<td>Learn how to pack a column.</td>
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<tr>
<td></td>
<td>Swelling a Gel</td>
<td>Learn how to pack a column.</td>
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<td></td>
<td>Packing a Low Pressure Column</td>
<td>Learn how to pack a column.</td>
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<td></td>
<td>Running a Low Pressure System</td>
<td>Learn how to pack a column.</td>
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<td></td>
<td>Preparing a Calibration Curve</td>
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<tr>
<td>Ion Exchange Chromatography</td>
<td>Buffer Preparation</td>
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<td>Swelling a Gel</td>
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<td>Packing a Low Pressure Column</td>
<td>Learn how to pack a column.</td>
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<td></td>
<td>Running a Low Pressure System</td>
<td>Learn how to pack a column.</td>
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<tr>
<td>Partitioning</td>
<td>Preparation of Phase Systems</td>
<td>Learn how to do a Liquid/liquid extraction.</td>
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<td></td>
<td>Mixing</td>
<td>Learn how to do a Liquid/liquid extraction.</td>
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<td>Calculation of Partition Coefficients</td>
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<td></td>
<td>Statistical analysis of the Results</td>
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<td>Isoelectric Focusing</td>
<td>Preparation of Gels</td>
<td>General lab skills.</td>
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<td>Running the Gels</td>
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<td>Documenting the Gels</td>
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<td>Cross-Flow Filtration</td>
<td>Preparing buffers and solutions</td>
<td>Learn about concentration polarization.</td>
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<tr>
<td></td>
<td>Running a Cross-Flow Filtration Unit</td>
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<td></td>
<td>Statistical analysis of results</td>
<td>Applied mass transfer principles to filtration.</td>
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<td>Calculation of Mass Transfer Coeff.</td>
<td>General lab skills.</td>
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<td>Dialysis</td>
<td>Preparation of Dialysis bag</td>
<td>Learn about diffusivity through porous media.</td>
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<td></td>
<td>Performance of Dialysis</td>
<td>Learn about diffusivity through porous media.</td>
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<td></td>
<td>Calculation of Diffusion Coefficients</td>
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\[ \text{TABLE 2} \]

<table>
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<tr>
<th>Laboratory</th>
<th>pH-meter</th>
<th>Balance</th>
<th>Conductivity meter</th>
<th>Micropipettes</th>
<th>Centrifuge</th>
<th>Spectrophotometer (Absorbance)</th>
<th>Spect. (Kinetics)</th>
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laboratory is very time intensive because washing between runs takes approximately 90 minutes. After the students have collected enough data, they use the equation below to estimate the mass transfer coefficient \( k \) and the membrane concentration \( C_{AW} \),

\[
J = k_0 \ln \frac{C_{AW}}{C_A^{b}}
\]

where \( J \) is the trans membrane flux in units of g/cm² min. and \( C_A^{b} \) is the concentration of the dextran solution in units of g/cm².

**PROJECT**

After they have completed the training part, the students start a project that consists of the purification of a biomacromolecule from some raw material. The genesis of each laboratory project is a research project that has been pursued in our own research group. Examples of projects included in our laboratory are: 1) the isolation of human antibodies from transgenic corn\(^{[6]}\); 2) the isolation of alcohol dehydrogenase from yeast\(^{[7]}\); 3) the isolation of coagulation factors from human plasma\(^{[8]}\); and 4) the fractionation of proteins present in the lenses of mammals\(^{[9]}\). Flow sheets of these processes are shown in Figures 1 to 4. During this portion of the semester the participation of the instructor is minimal. The students are responsible for the procurement of supplies, for the disposal of waste, and for their own working hours. Their objective is to finish their projects successfully. Because they have been trained before they start their projects, it is their responsibility to repeat unsuccessful experiments on their own time. The projects are described to them, but they are expected to explore different operating conditions to determine the effect of those changes on yield and purity. After the students have become familiar with the project (by reading a couple of key articles in the open literature), they discuss with the instructor the kind of experiments they want to conduct and what kind of conditions they would like to explore. A few projects are described below.

A number of different separation techniques are used to isolate \( \gamma \)-crystallins from whole calf lenses. The sequence of steps to purify the \( \gamma \)-fraction that is used routinely in our laboratory is the following\(^{[9]}\): 1) cell disruption; 2) centrifugation; 3) size exclusion chromatography; 4) dialysis; 5) ion exchange chromatography; 6) dialysis; and 7) freeze drying. The students characterize the preparation, explore new separation conditions (for example, new salt gradients in the ion-exchange step or different lengths of size exclusion columns), and study the proteins using static and dynamic light scattering. Good samples that are not used by the students are recycled into our research group. This laboratory requires some specialized equipment such as a bench-top or floor centrifuge able to accommodate 50 mL tubes, a low-pressure chromatography system, and a spectrophotometer. The freeze dryer is optional. Because this specialized equipment comes at significant cost, certain pieces can be replaced by cheaper alternatives. The low-pressure chromatography system can be replaced by some of its individual components, such as a flow-cell spectrophotometer and a fraction collector. The pump of the chromatography system can be replaced by flow under gravity using a two-compartment gradient former. To minimize the costs of the most expensive materials in this experiment, the chromatography gels (Sephadex G-75 and Sephadex C-50), we usually recycle gels from one year to the next without major problems. The low-pressure columns are quite cheap in the sizes that we use (either 1.4 or 2.5 cm in diameter columns). All other expendables are cheap. The lenses may be bought from specialized vendors or from the local slaughterhouse. The latter has the benefit that the lenses can be obtained for free or relative low cost, while the former allows one to buy lenses of various ages. This could be beneficial as the students can then explore variations in the composition of the lenses as a function of animal age.

Another project is comprised of the synthesis and purification of
small peptides. The students learn how to synthesize a peptide using a solid state synthesizer, how to isolate the peptide by precipitation, and how to identify (and further purify) the product by reverse-phase chromatography. The basic pieces of equipment are a solid-state synthesizer, a high-speed centrifuge, a High Pressure Liquid Chromatography (HPLC) instrument, and a freeze dryer. The students are asked to explore different separation protocols in the reverse-phase chromatography isolation of the target peptide. In addition, the students use a dynamic light-scattering instrument to determine the thickness of the peptide-adsorbed layer on polystyrene latex with different surface chemistries. This particular laboratory is relatively expensive because high-pressure chromatography systems able to process hundreds of milligrams of peptides and the solid-state peptide synthesizer are normally not found in a regular unit operations laboratory. The study of the behavior of these peptides at solid/liquid interfaces requires a particle-sizing instrument. In our laboratory, we use a backscattering dynamic light-scattering instrument from Brookhaven that has proven to be quite rugged and very easy to use, and is reasonably cheap.

A few years ago, we began exploring the isolation of human antibodies expressed in corn. The main objective of our work was to find suitable alternatives to the use of a protein A column, by far the most expensive element in the purification of antibodies. We have developed a new process by which human antibodies expressed in corn are isolated to high purity and yield using aqueous two-phase extraction. We have found that one or two extraction steps, where the target antibody concentrates in the bottom or top phase, followed by a second extraction step, where the target antibody precipitates at the interface, yield the best results. The optimum purification protocol consists of the following steps: 1) extraction of the antibody (and contaminating proteins) from cornmeal using a NaCl solution; 2) addition of PEG and a salt to a concentration high enough to induce the formation of two liquid phases at equilibrium; 3) removal and disposal of the upper phase (PEG-rich); 4) addition of PEG to the bottom phase to create a second ATPS; 5) recovering of the antibody from the new liquid/liquid interface; 6) removal of the excess salt by diafiltration; and 7) polishing of the product by protein A chromatography.

The students in this laboratory extract the antibody from cornmeal and then study its partitioning behavior in a variety of aqueous two-phase systems. This particular project is well suited for the statistical design of experiments. The equipment needed is quite standard. In addition to basic laboratory equipment, the students need a rotary mixer, a spectrophotometer, an HPLC system, and a centrifuge. The raw material in our case is cornmeal containing a particular human antibody. Of course, most programs will not have access to that raw material. One option is to use commercial cornmeal spiked with a commercial IgG. Another option is to spike the cornmeal with hemoglobin rather than an antibody. Hemoglobin from pigs is quite cheap and its presence may be detected by its absorbance at 450 nm. Thus, it is possible to measure total protein content by a colorimetric assay and hemoglobin concentrations by UV spectroscopy. In addition, the students need PEG of various molecular weights and various salts. The cost of the equipment varies depending on the approach. If the experiments are done with antibody-spiked cornmeal, the main cost is a protein A column and the corresponding chromatography hardware. If the experiments are done with hemoglobin-spiked cornmeal, the cost is very low. The aqueous two-phase systems by themselves are very cheap, particularly if dextran is replaced with a salt like phosphate or citrate. Most labs have a centrifuge and a spectrophotometer. Even in the absence of a centrifuge, the systems can be allowed to separate under gravity. Details of this project are described in the following section as an example.
EXAMPLE: ISOLATION OF ANTIBODIES FROM CORNMEAL

When macromolecules, such as proteins, are dissolved in a two-phase system, they selectively distribute between the phases. A partition or distribution coefficient is defined by

\[ K = \frac{C_t}{C_b} \]  

where \( C_t \) and \( C_b \) are the concentrations of the protein in the top and bottom phases, respectively. The partition coefficient depends on the pH of the phases, temperature, type, and concentration of salt added, and type and concentration of the polymers used as the phase-forming species. The fact that the partition coefficient is a function of so many variables makes this project particularly suited for optimization studies. For example, the students may choose three molecular weights of PEG, three different salts (varying in their chaotropic properties), and three values of pH (near, above, and below the isoelectric point of the protein). A three-level full factorial experimental design will consist then, of 27 experiments. Because duplication is a necessity in this type of experiment, students need to prepare, sample, and analyze 54 extraction experiments.

Materials
PEG of various molecular weights (for example, 3,500, 8,000, and 20,000), dextran, acetate and phosphate buffers spanning three values of pH (near, above, and below the isoelectric point of the protein). The fact that the partition coefficient is a function of so many variables makes this project particularly suited for optimization studies. For example, the students may choose three molecular weights of PEG, three different salts (varying in their chaotropic properties), and three values of pH (near, above, and below the isoelectric point of the protein). A three-level full factorial experimental design will consist then, of 27 experiments. Because duplication is a necessity in this type of experiment, students need to prepare, sample, and analyze 54 extraction experiments.

Equipment
Spectrophotometer or plate reader, centrifuge (optional), magnetic stirrers, hot plates, balances, pH meter, micropipettes, rotary shaker (optional), and ultrafiltration cell (optional).

Methods
“Extraction” of antibody from cornmeal
1. Extract 1 g of cornmeal with 10 ml of 150 mM NaCl for 8 to 12 hrs at 4 °C with stirring.
2. Remove the solid particles by centrifugation at 9,600 g for 1 hr at 4 °C.
3. Filter the supernatant through filter paper.
4. Filter again through a 0.45 µm membrane.
5. Add 1 mg/mL pig hemoglobin to this extract.
6. Determine total protein using the Bradford or BAC tests.

Preparation of Stock Solutions
A) Dextran (30% w/w)
1. Weigh 30 g of dextran into a bottle.
2. Dissolve the dextran in 30 g of deionized water.
3. Mix the above, it will make a paste.
4. Add the remaining 40 g of deionized water.
5. Heat the solution up to 95 °C to facilitate dissolution of the polymer.

B) PEG (50% w/w)
1. Weigh 25 g of PEG into a bottle.
2. Dissolve the PEG in 25 g of deionized water.

Preparing the Phase Systems
1. Shake the stock solutions.
2. Place a 15 mL centrifuge tube on a balance.
3. Weigh out the desired amounts of stock solutions into the tube in the order of increasing densities.
4. Add enough buffer (blanks) or buffer plus 1 g of cornmeal extract to complete 10 g.
5. Mix the contents of the test tube thoroughly, first by hand, and then in a rotary shaker for 20 minutes.
6. Centrifuge the tubes for 15 minutes at 1500 x g to allow the phases to separate.
7. Sample the phases as described below.
8. The pH in each phase is measured with a microelectrode directly on the undiluted phases. Because of the high viscosity of the phases, the pH measurements must be done over a relatively long period of time.

Sampling and analyzing the phases
1. Carefully pipet 2 g of the top phase.
2. Carefully pipet 2 g of the bottom phase.
3. Leave the separated phases to rest and stir again. Inspect the solution to detect density differences along the axial direction of the test tube.
4. Read the absorbance of each phase sampled at 450 nm.
5. Perform the Bradford assay for each phase.
6. If readings are out of range then dilute the samples with buffer. This step can be done by volume rather than weight.
7. Calculate the partition coefficient of pig hemoglobin and the overall partition coefficient for each sample. Partition coefficient is reported as

\[ K = \frac{A_t^T - A_t^B}{A_b^T - A_b^B} \]  

where \( A_t^T, A_t^B, A_b^T, A_b^B \) are the absorbencies of the sample in the top and bottom phases and the absorbencies of the blank in the top and bottom phases respectively.

Results
The students process the raw adsorption data from the Bradford test and from the absorbance data taken at 450 nm. The students need to discount the proper blanks and must account for dilution factors. The absorbance values are then converted into concentrations using the appropriate calibration curves. These values plus the values of the masses of each phase, which can be calculated through the use of well-established correlations for densities of PEG and dextran solutions, are
used to calculate recovery. Concentration values from Bradford (total protein) and absorbance at 450 nm (hemoglobin) are used to calculate purity and purification fold. Finally, the partition coefficients (total protein and target protein) are calculated and reported.

The partition coefficient data may be regressed to find a correlation between the partitioning coefficient with pH and PEG molecular weight for all salt types. Calculated and experimental partition coefficients are plotted in Figure 5.

LABORATORY ORGANIZATION

The students in the class are divided into groups that pursue different projects. This is necessary because of equipment availability in our laboratory. The number of students in each group varies from year to year depending on the number of students in my course. During the training sessions, groups are small, no larger than three students per group. During the project portion, group size ranges from two (in years with few students) to five (in years with a large student population). One student in each group is chosen as the group leader who is responsible for distributing work and reporting to the instructor. The expectations in each case also change. For example, members of small groups (i.e., two students) are expected to actively participate in each task of the project, but they are not asked to explore a variety of operating conditions. Students belonging to larger groups are normally divided into two or three subgroups with very specific tasks. For example, in the isolation of alcohol dehydrogenase project, a large group of five students will be divided into three subgroups. A group of two will be in charge of cell growth and disruption and will explore how different metabolic stages of the yeast affect the production of the enzyme. They may also explore different milling conditions. The second group of two students will be in charge of process-separation development and the remaining student will be in charge of all the analytical work (i.e., determination of protein concentration and enzymatic activity in each step of the process). The group organizes its own tasks and the lab is run on an “open door” policy (including nights and weekends). Graduate students working in the author’s laboratory help in keeping the lab open at unusual hours and they provide the “adult” supervision that an undergraduate student should have.

CONCLUSIONS

A unique approach to teaching an undergraduate laboratory has been developed. The key feature of our approach is the splitting of the semester into two sessions: Training and Project. The training section builds the students’ basic laboratory skills. The project section incorporates research projects into the undergraduate curriculum. The students benefit because they are exposed to state-of-the-art techniques, using equipment bought with research funds. In exchange, they contribute to a project by, for example, optimizing a particular separation or by producing materials that are fed into our research group. The students’ reactions may be mixed. Some of my students have used the expression “research laboratory” in a positive way while some others use it as a critique, mostly referring to the number of hours that they are expected to spend in the lab. The acceptance of our approach by the students changes from year to year and depends heavily on their quality.

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Figure 5. Calculated vs. experimental partition coefficient.
SEPARRATIONS: A SHORT HISTORY
AND A CLOUDY CRYSTAL BALL

PHIL WANKAT
Purdue University

Separations have always been and will continue to be critically important in the processing of chemicals. It is common to note that 40 to 70% of both capital and operating costs in industry are due to separations. It has been estimated that 15% of the world’s energy use is required by separations. Because of their industrial importance separations have always played an important part in chemical engineering education and in the chemical engineering literature.

HISTORY OF SEPARATIONS

The beginning of separations apparently occurred before recorded history. Egyptians used filtration to filter grape juice over 5,000 years ago. Aristotle mentioned that pure water can be obtained by evaporating sea water. A combination of coagulation of impurities, evaporation, and crystallization used for salt manufacture were commonly in use by the 16th century. Similar practices were still in use in India in 1980. Pressing, evaporation, and crystallization were commonly in use for sugar production by the 16th century.

Distillation, particularly batch distillation, has a long history. Mesopotamian clay distillation vessels with lids shaped to collect the condensed volatile distillate have been dated to ~3500 BCE. Alchemists in the first century AD in Alexandria used a variety of simple batch stills or retorts. The alembic still was invented by Jabir ibn Hayyan (aka Geber) in the late 8th or early 9th century. Similar stills are currently in use in some whiskey distilleries and for distilling rose oil. By the 14th century the production of strong alcoholic drinks had become an industry. The first book on distillation was Hieronymus Brunschwig’s Liber de arte distillandi published in the early 1500s and translated into English in 1527. Brunschwig’s book (Figure 1) is an apothecary with distillation used to produce various medicines from plants. Petroleum distillation was started in England in the 17th century and coal tar distillation was first patented in 1746. Fractionation of coal tar into naphtha, kerosene, lubricating oil, and paraffin was patented in England in 1850. The first oil refinery constructed in 1860 in Pennsylvania used simple batch stills and collected wide-boiling fractions as the distillation proceeded.

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

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Figure 1. Cover page to Hieronymus Brunschwig’s Liber de arte distillandi. Courtesy of Donald F. and Mildred Topp Othmer Library of Chemical History, Chemical Heritage Foundation, Philadelphia, PA.
Horizontal stills with improved performance were used in the early 19th century for alcohol purification. An improved still was developed in 1818 by Cellier in France who developed a vertical bubble plate still for alcohol purification. In Victorian times large estates often had batch distillation systems to prepare drugs and concentrated liquors. Popular books on distillation were available for this market.

In his Handbook of Chemical Engineering, published in 1901 and in an enlarged edition in 1904, George Davis clearly developed the unit operations idea (not by this name) for distillation. Before this, the distillation of each chemical was studied separately. It is notable that the 2nd edition of C.S. Robinson’s The Elements of Fractional Distillation has elements of both the unit operations generalization and individual chapters for distillation of a number of chemicals such as ethanol. By the fourth edition, extensively revised by Ed Gilliland, the unit operations approach dominated and distillation of specific chemicals were relegated to examples. The Elements of Fractional Distillation may have been the first chemical engineering book to also become popular with a nontechnical audience—it was very popular with bootleggers in the 1920s and 1930s.

The first continuous distillation appears to have been developed by Aneas Coffey in 1830. He developed a vertical perforated plate column for alcohol purification (Figure 2). This still was equipped to preheat the feed by exchange with the condensing distillate and the bottoms. Davis shows open-steam distillation systems and several examples of methods to reduce energy. In 1900 vertical perforated plate columns quite similar to modern equipment were introduced for distillation of tar. Safety in tar stills is discussed by Davis, who notes that safety valves are useful if they are kept in working order. Packing was apparently first employed in 1820 and was patented in 1847. The problem of breaking the ethanol-water azeotrope was solved by Young in 1902 with a batch, azeotropic distillation process using benzene as the entrainer to produce the first observed ternary azeotrope as the distillate product. The batch process was converted to a continuous azeotropic distillation by Keyes in 1928.

In the early 1920s petroleum refineries had not adopted more modern fractionation systems and were using horizontal stills directly heated on the bottom in conjunction with partial condensation to distil petroleum. These systems were not very efficient and considerable redistilling was required. Modernization of distillation in refineries occurred in the 1920s when W.K. Lewis was hired as a consultant by the Standard Oil Company of New Jersey and introduced vertical fractionation systems. By the 1920s and 1930s the schematics of continuous distillation columns in textbooks and in Perry’s Handbook look fairly modern except that valve trays and structured packings had not been invented yet. Heat recovery in distillation was common by 1923. The histories of distillation equipment, distillation control, and azeotropic and extractive distillation were reviewed by Fair, Buckley, and Othmer respectively, for the 75th anniversary of AIChE.

Theoretical analysis of continuous binary distillation was first achieved by Sorel, who was interested in the distillation of alcohol. Sorel’s method is accurate, but confusing and laborious since a trial-and-error calculation was required on every stage. Binary distillation was analyzed graphically without trial-and-error by Ponchon and Savart independently. Lewis realized that in many cases the vapor and liquid molar flow rates are approximately constant—if they are assumed to

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William Gossage used an old windmill as a tower to absorb HCl in a downward-flowing stream of water. The column was packed with gorse and brushwood. This inspiration soon led to towers packed with various materials such as twigs, broken brick, coke, and stone to absorb HCl. A next step was the development of high efficiency CO₂ absorption towers by Ernest Solvay for his Solvay process.\[14, pp. 29-30\] The need for good distribution of the gas in the tower was known by 1902.\[11, p. 201\] Theoretical analysis of absorption was facilitated by Whitman’s development of the two-film theory of mass transfer.\[52\]

Unlike distillation, which developed gradually over centuries, practical application of absorption appears to have been developed solely by a single person in 1836.\[14, p. 29-30\] William Gossage used an old windmill as a tower to absorb HCl in a downward-flowing stream of water. The column was packed with gorse and brushwood. This inspiration soon led to towers packed with various materials such as twigs, broken brick, coke, and stone to absorb HCl. A next step was the development of high efficiency CO₂ absorption towers by Ernest Solvay for his Solvay process.\[14, pp. 29-30\] The need for good distribution of the gas in the tower was known by 1902.\[11, p. 201\] Theoretical analysis of absorption was facilitated by Whitman’s development of the two-film theory of mass transfer.\[52\]

Liquid-liquid extraction became an important laboratory method in the mid 19th century, and the concept of partition ratios was introduced by Berthelot and Jungfleisch in 1872.\[33\] Industrial applications started about this time. In 1883 Goering patented a countercurrent extraction process for recovery of acetic acid, and in 1898 Pfleiderer patented a stirred column extractor.\[33\] With the development of chemical engineering as a profession in the early 20th century, extraction benefited from many of the improvements originally devised for distillation and absorption. Development of new aqueous two-phase extraction systems has allowed purification of proteins that are likely to be unstable in organic solvents.\[14, p. 423\] Treybal\[35, p. 425\] notes that extraction is “a relatively immature unit operation. It is characteristic of such operations that equipment types change rapidly, new designs being proposed frequently and lasting through a few applications only to be replaced by others. Design principles for such equipment are never fully developed . . .”

Crystallization from solution was one of the key tools of the alchemists.\[36\] was an important unit operation at the end of the 19th century,\[11, p. 266\] but remains partly art. In 1878 Gibbs studied the thermodynamics of growing crystal surfaces at equilibrium and realized that thermodynamics was often not sufficient to explain the crystal growth.\[36\] McCabe found that the deposition rate/unit area is often linear in supersaturation and deposits grow at a uniform rate. Unfortunately, McCabe’s law often does not hold.\[36\] Industrial scale crystallizers in 1934 did not look very different than many modern crystallizers. The importance of crystal size distribution was developed by Randolph and Larson.\[39\] Hulbert\[38\] reviewed crystallization for the 75th anniversary of AIChE, and more recent advances in crystal engineering are reviewed by Doeherty.\[40\] Precipitation is similar to crystallization except the product is usually amorphous with a poorly defined shape and structure. Precipitation is often used as a first cut before crystallization. Early workers did not delineate between precipitation and crystallization and many early crystallizations would now be classified as precipitation.

Membrane filtration developed at least as early as 1600 BC when the Arawak people of the West Indies used porous stone filters to purify drinking water.\[41\] With this exception, the development of membrane separations is almost unique since the science was developed before practical applications. The first studies of membrane phenomena were done by Abbé Nollet in 1748 who studied permeation through a semipermeable membrane.\[42, pp. 80\] In 1855 Fick studied diffusion and developed the laws of diffusion still used to study membranes.\[42, pp. 80\] Thomas Graham studied dialysis in 1854 and dialysis using parchment paper for the membrane was practiced commercially for processing beet sugar at the end of the 19th century.\[11, p. 266\] The major current application—the artificial kidney—was developed in 1944 by Kolff and Beck.\[42, pp. 95-97\] Graham studied gas separations in 1863 but it was not until 1954 that Kolff and Balzer developed a membrane lung oxygenator that was improved by the work of Clowes and coworkers.\[42, pp. 131-133\] Pauli developed electrodialysis in 1924 and the multicell electrodializer was developed in 1940.\[42, pp. 98-99, 40\] but electrodialysis did not become practical until the 1950s with the development of synthetic ion-exchange membranes.\[42, p. 100\] Currently, industrial applications of electrodialysis are uncommon, but there is interest in use of it as part of a hybrid process.\[42\] The seminal development that led to large-scale commercial applications of membranes for pressure-driven systems was the Loeb-Sourirajan method of producing asymmetric membranes with a defect-free thin skin.\[42, pp. 104-105\] This method rapidly led to commercial reverse osmosis systems in the 1960s.\[42, pp. 104-105\] Loeb-Sourirajan membranes could also be used for ultrafiltration (UF) if the membranes were not annealed. This led to commercial UF systems, but they were severely hampered by concentration polarization. The eventual understanding of concentration polarization led to the development of flow regimes and membrane modules that allowed for practical applications of UF in the mid to late 1960s.\[42, pp. 117-125\] After Henis and Tripodi at Monsanto developed the Prism membrane separator for hydrogen pu-
rification in 1979, several other commercial gas permeation systems were developed. Pervaporation can be traced to the work of Graham, but the definitive studies were done by Binning and his co-workers in the late 1940s and early 1950s. Pervaporation was first commercialized in the 1980s for breaking the ethanol-water azeotrope.

Adsorption, particularly the use of charcoal to purify water, has been known since Biblical times, was used commercially in the late 18th century for the clarification of raw sugar, and was recommended for purifying water in an 1859 Western US guide book. Scheele studied the adsorption of gases on charcoal in 1773, and the ability of charcoal to remove odors from air was extensively studied by Hunter in the 1860s. Clay was also extensively used with an early use in “fulling” (the removal of grease from wool—hence the name fuller’s earth) and processing large-scale ion exchange systems, particularly for water treatment. Adsorption, particularly using charcoal, has been known since Biblical times.

Liquid chromatography in the form of column elution chromatography was first developed by Tswett in 1903. He called the method “chromatography” because he observed colored bands moving down the column. Large scale applications of very similar systems were commercialized in the late 1940s for separation of carotene, xanthophyll, and chlorophyll on an activated carbon column using gradient elution and backwash, and in the 1950s the Arosorb process developed by Sun Oil Co. was used to separate aromatics from alkyl hydrocarbons using silica gel. Currently, commercial applications of liquid chromatography are common for bioseparations. Liquid-liquid chromatography (LLC) was developed by Martin and Synge and gas-liquid chromatography was developed by James and Martin. Although very successful in analytical applications these methods are less successful in large-scale systems. LLC led to bonded phases that are used commercially in large-scale systems, however. Scale-up of size exclusion chromatography (SEC) was successful, and SEC was used for large-scale separations shortly after it was invented. Although affinity (or bioaffinity) chromatography, which is used for purification of antibodies and proteins, has been traced back to Starkenstein’s isolation of α-amylase on starch in 1910, modern applications started in the 1950s with the work of Lerman’s group and were popularized by a series of papers by Cuatrecasas and Anfinsen. Large-scale applications (large-scale is a relative term and may refer to a 50 mL column processing 15 liters of fluid) were started in the early 1980s. Although many commercial units are not large, the value of the purified product can be significant.

Electrophoresis, which is also extensively used for protein purification on a small scale, has a long history, but modern electrophoresis was initiated by the experimental work of Arne Tiselius in 1937 and the development of a theory for electrolyte diffusion by Debye and Hückel. Tiselius’ original method, paper electrophoresis, was limited by being able to collect pure samples of only the fastest positively and negatively charged components and convection caused by electrophoresis was limited by being able to collect pure samples of only the fastest positively and negatively charged components and convection caused by electrophoresis often reduces the separation. Gel, membrane, and paper electrophoresis were developed to control convection. If the electrophoresis is done in the presence of a pH gradient the result is isoelectric focusing, which has considerably more separation power. Isoelectric focusing was developed by Kolin in the mid-1950s and further developed by Svensson. Preparative methods of electrophoresis and isoelectric focusing often employ two-dimensional approaches, but applications remain small-scale although a few researchers continue to work to scale-up the systems.

After reviewing the historical development of separation techniques, I conclude that the two most important long-term developments were distillation and membrane separators.

1. Distillation. Despite modest separation factors, distillation’s ease of staging as a countercurrent process with extensive reuse of energy separating agent plus use of reflux
and boilup allow one to obtain high purity and high recovery without the addition of a mass separating agent. The major downside for distillation is high energy use. Azeotropes and low relative volatility limit applications, although the addition of a mass separating agent often allows circumvention of these limits.

2. Membrane separators. Asymmetric hollow-fiber membranes with high selectivity have an extremely high area to volume ratio, very low energy use, and can achieve high purities. The downsides for membrane separators is the difficulty of staging and the lack of reuse of energy separating agent make achieving both high recovery and high purity expensive. Concentration polarization and fouling currently limit applications for liquids.

TEACHING SEPARATION PROCESSES

The key questions remain, What to teach? and, How to teach it? If we had as much time as was needed, we could teach all the separations in a separations-oriented ChE curriculum that includes core courses in phase equilibrium, equilibrium-based separations, solids/mechanical separations, and rate-based separations; and electives in advanced equilibrium-based separations and in novel/unalso separations. This process-oriented curriculum uses separations as the unifying theme, but it does not fit into current trends in curriculum development.

With an overcrowded curriculum separation methods are not going to receive significantly more time; thus, we must choose which separations to include. At Purdue we currently have one core course in separations. In this junior-level course I cover flash distillation, normal and complex continuous distillation (binary, multicomponent, extractive, and azeotropic), batch distillation, absorption and stripping, liquid-liquid extraction, and membrane separations. The course has two lectures and a two-hour, AspenPlus computer laboratory every week. To cover this significant amount of material, extraction is taught at a purely equilibrium level with no design, and membranes are usually limited to gas permeation (but including all flow patterns). I use my own textbook, although there are other good textbooks available. [The outline of this course is available from the author at wankat@purdue.edu.] Obviously, this choice of material leaves out many important separation processes. Some of these are included in senior laboratory (e.g., drying and chromatography) or senior design courses, but the students rarely have the same level of understanding of theory. It is also important, if possible, to have dual-level (graduate and undergraduate) electives available on topics such as particulates, rate separations, bioseparations, or advanced distillation.

For distillation and the other equilibrium-staged separations, process simulators are used for design and simulation in industry and thus should be used in undergraduate courses. The particular process simulator used is not critical. Spreadsheets can be used for membrane systems. Spreadsheets, MATLAB, and Mathematica are useful for solving problems and helping students understand the equilibrium-staged separation methods. If students have not been trained in these tools, class time must be set aside to teach students how to use the tools—preferably in a computer laboratory. Use of these tools also helps graduates satisfy ABET’s criterion 3k, “an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.” Simulators should also be used in dual level electives. The “lecture” portion of the courses should use well known active learning methods in addition to mini lectures.

PREDICTIONS

Where are industrial use, education, and research funding for separations headed? My crystal ball is cloudy, but I will hazard predictions. These predictions assume that the one great “killer” application that makes a host of existing separation processes obsolete will not appear and that funding for academic research on separations will remain tight despite the identification of a number of high-priority research areas in separations.

First prediction: Distillation will remain the major industrial workhorse and a major, although probably slowly declining, part of education in separations. Education in distillation (including absorption and stripping) will increasingly focus on the use of process simulators. Unfortunately, funding for academic research on distillation will remain anemic in the United States.

Rationale – Industrial Use: Distillation will continue to be the industrial workhorse because: 1. Distillation is trusted. 2. It is understood well enough that existing computer models will produce designs that work in about 80% of cases. 3. Except for extractive and azeotropic distillation, mass separating agents are not required and thus do not need to be recovered. 4. A complete binary separation is possible, which means a component can be recovered with high purity and high recovery. 5. In many cases distillation is the most economical separation process. 6. Currently, 90-95% of all separations in the chemical process industry are done by distillation.

Rationale – Education: Because of the broadening of positions that graduates accept, most schools want to prepare students for jobs outside the traditional chemical and petroleum industries. Thus, there is considerable pressure to teach other separations, but additional time is rarely allocated to separation processes. Process simulators will be used because they prepare students for industrial practice, they are now readily available at most schools, they are supported by textbooks, ABET encourages the use of modern tools, and they help students learn.

Rationale – Research Funding: The U.S. funding agencies have to a considerable extent apparently decided that distillation is a known art and that companies or Fractionation Research Inc. (FRI) should conduct any research needed.
This reasoning ignores that even small advances in distillation can be economically important, and that a paradigm shift, although perhaps unlikely, would have enormous economic impact.

**Second prediction:** Mechanical separations such as flotation, filtration, centrifugation and settling will continue to be ignored in the ChE core at most schools although they will remain critically important in industry. Funding for research in particulates will remain reasonably secure.

**Rationale – Industrial Use:** Because unwanted solids must be removed and many products are sold as solids, particulate separations will remain industrially important.

**Rationale – Education:** Unfortunately, at the time that the engineering science revolution changed chemical engineering education, many steps in handling and processing solids were added not science. These unit operations were often dropped from the curriculum since they were not considered to be scientific. Many schools have added these processes back into the curriculum, but in an elective course on particulates instead of in the core. Because of time pressures on the core, mechanical separations are unlikely to be added to the core in a meaningful way.

**Rationale – Research Funding:** The mechanical separations have found a home in the general area of funding for particulates. Although not overly generous, this funding is probably secure.

**Third prediction:** Membrane separation processes will continue to find industrial applications, but at a slower rate than predicted by researchers. Membrane research will continue to benefit from support that is modest, but robust compared to that received by other areas of separation. Membrane separations will become an increasingly common part of separation courses in the ChE core.

**Rationale – Industrial Use:** In applications where they work well (high selectivity and high flux, commercially available, high purity or high recovery is required, minimal fouling occurs, and the membrane has a long life) membranes are often the most energy efficient and least expensive separation method by far. Unfortunately, these limitations currently limit use of membranes, but additional research is likely to slowly broaden the range of applications.

**Rationale – Education:** Since industry is using membrane separations more and since many academics are doing membrane research, there is a desire to cover this material. Membrane separators are now included in many textbooks, and the level of presentation is accessible to undergraduate chemical engineering students.

**Rationale – Research Funding:** Funding agencies appear to believe that the major membrane successes in water treatment and medical applications can be repeated even though the context may be different. So far, the tendency of membrane researchers to be overly optimistic about the rate of commercialization of new membrane applications has not cut into support, and membrane separators remain the only separation systems that are funded at close to a reasonable level.

**Fourth prediction:** Adsorption, ion exchange, and chromatographic separation processes will slowly become more important in industry and will continue to receive modest research support, particularly for biological applications. These processes will be taught mainly at the graduate level. Their lack of coverage at the undergraduate level will continue to serve as a barrier to their wider application in industry. Research funding will remain tight although it will be somewhat more available for biological applications.

**Rationale – Industrial Use:** Adsorption, ion exchange, and chromatographic separation processes can often accomplish separations more economically than other methods. This is particularly true in biological applications where distillation is not applicable. Because most engineers with a B.S. degree are unfamiliar with these processes, however, they will be unlikely to consider sorption separations for new applications.[8] [16]

**Rationale – Education:** Since the sorption separations are batch processes that require mass transfer calculations, they are inherently more difficult to understand than steady-state, equilibrium processes. Because many undergraduate chemical engineers have considerable difficulty understanding them, these processes will be taught mainly to graduate students.

**Rationale – Research Funding:** Money will be available for materials applications to make new sorbents, particularly if the research can be tied to nanotechnology. Biological applications have more sources of funding available than nonbiological applications such as gas processing.

**Fifth prediction:** Crystallization (and precipitation) will continue to be used in many industries where it is critically important. Crystallization will remain an orphan without a home, however, in the core of most undergraduate curricula. Crystallization research is currently underfunded and is unlikely to receive large increases.

**Rationale – Industrial Use:** Since many products are sold in a solid form, the final processing step is often crystallization. In addition, many products such as salts and other nonvolatile materials use very large-scale crystallization. These processes are not going to disappear.

**Rationale – Education:** Crystallization can be analyzed as an equilibrium staged separation, but the equilibrium is not the VLE that undergraduates and professors are familiar with. A complete analysis that predicts the crystal size distribution requires a mass transfer analysis coupled with population balances. This material is accessible to undergraduates, but because population balances are usually not covered elsewhere in the undergraduate curriculum, considerable time needs to be devoted to the topic. Even complete coverage of population balances only begins to cover the idiosyncratic nature of crystallization. Because of competing pressures to cover other material, most schools will not carve out the time required in the undergraduate
core despite a call to make crystalline solids one of the core themes in the curriculum.\(^{[60]}\) Thus, at most schools thorough analysis of crystallization will only be done in elective courses when there is a professor interested in teaching this material. Most ChE graduates have a weak background in crystallization and solids handling in general,\(^{[60]}\) and this unfortunate condition is predicted to continue.

**Rational – Research Funding:** Much of the funding for crystallization was based on the promise of applications in space. This source appears to have largely dried up and no large-scale replacement sources have materialized.

**Sixth prediction:** Extraction will continue to be important in industry and to be covered in undergraduate courses, but not enough time and energy will be focused on the unique extraction design issues in education. No prediction will be made on research funding.

**Rationale – Industrial Use:** Extraction is very useful for cases where distillation does not work. Many of these applications of extraction such as separation of nonvolatile compounds are industrially important.

**Rationale – Education:** Although crystallization is probably the most idiosyncratic equilibrium-staged separation process, extraction is a close second. Important content such as third-phase (or rag) formation and design of different types of extractors receives minimal or no coverage in most undergraduate programs. Complete coverage of the methods used industrially would require a separate course. Because of time pressures on the curriculum, this will not happen in the required core. In addition, most current textbooks do not cover, and most professors teaching separations are not familiar with, these details.

**IS THERE A BETTER WAY TO ALLOCATE RESEARCH FUNDING?**

A rational way to allocate funding for separations research could be based on the potential for impact. Impact can certainly come from major advances such as the Loeb-Sourirajan method of producing asymmetric membranes, but it can also come from relatively small advances that are very widely applied. Hypothesize that impact potential can be approximated as,

\[
\text{Impact Potential } \alpha (\text{potential research advances}) \times (\text{market for separation method})
\]

The market is the current use of the separation method measured in value of products or in cost of the separation units. In either case market can be estimated reasonably accurately for separation methods currently in use. [Other evaluation methods would have to be used to analyze rare proposals for separation methods that are totally novel where there is no current use.] Potential for research advances is much more difficult to estimate. Perhaps a start can be obtained by using an updated version of George Keller’s plot of use maturity versus technological maturity.\(^{[51]}\) If technological maturity is normalized to scale from 0 to 1, then we can hypothesize that

\[
\text{Potential for research advances } \alpha (1 - \text{Technological Maturity})
\]

Then,

\[
\text{Impact Potential } \alpha (1 - \text{Technological Maturity}) \times (\text{market for separation method})
\]

This model is a guide for setting funding levels but still leaves significant room for individual judgments and modifications such as the use of weighting factors for potential and market.

Let’s qualitatively consider how three industrial separation methods would fare with this approach. According to Keller,\(^{[51]}\) distillation is technologically mature and is close to the technology asymptote; thus, the potential for research advances is low. Since the market is huge, however, Eq. (3) shows that the impact potential of additional research is relatively large. Thus, funding should be increased from its current very low level. Membrane systems have a lower technological maturity (higher potential) than distillation\(^{[51]}\) and a significant market; thus, funding for membrane research will remain high. Solvent extraction has a somewhat lower technological maturity than distillation,\(^{[51]}\) which implies a somewhat
higher potential, but the market is about 1/20th as large in the process industries [89, p. 29]; thus, funding would be lower than for distillation.

**CLOSURE**

Since reactors and separators are the core of chemical engineering, these aspects are important in the history, the current practice, and the future of chemical engineering. The history of separations helps explain how the current practice of chemical engineering separations and of separations in chemical engineering education evolved, and the history provides a useful, but probably limited, crystal ball to predict the future.

**ACKNOWLEDGMENT**

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Engaging Undergraduates in an Interdisciplinary Program: DEVELOPING A BIOMATERIAL TECHNOLOGY PROGRAM

JIA-CHI LIANG, SHIEH-SHIUH KUNG, AND YI-MING SUN
Yuan Ze University • Chung-Li, Taiwan

With the recent popularization of interdisciplinary studies, higher education has faced the challenge of engaging students in interdisciplinary learning and of requiring college teachers to cooperate to reach the goal of interdisciplinary teaching. “Interdisciplinary” means the mingling of several traditionally distinct disciplines to create a unified product, such as a course, a paper, or even a curriculum.\(^1\) According to the report, “Engineering Education for a Changing World (A National Action Agenda for Engineering Education),” a successful college student should have the abilities of group cooperation, communicative competence, and an understanding of the economic, social, environmental, and international context of their professional activities.\(^2\) To meet the demand for innovative engineering education, many schools now offer novel interdisciplinary curriculum programs. For instance, Texas A & M University and Arizona State University combined English with the freshman-engineering curriculum to improve students’ reading, writing, and communication abilities while they are studying engineering.\(^3\) Drexel University similarly merged humanities with the curriculum of the college of engineering, leading to student assignments such as using a poem to illustrate how to operate an experimental facility in an engineering laboratory.

While Biology previously was regarded as an independent subject, in recent years Life Science and Biotechnology have become increasingly interconnected with other subjects. Many of the breakthroughs in the field of Life Science and Biotechnology are actually the result of injecting technology research from other fields into these programs. And so for chemical engineering, a goal is to develop students’ ability to apply engineering principles to biological systems.\(^4,5\) Integrating chemical engineering and biological discoveries, however, has not been discussed extensively. For instance, the role of chemical engineering technology in the development of Biotechnology products typically occurs middle- and downstream of product development. Without a well-developed chemical engineering technology (separation, purification, and recovery), it is difficult to scale-up biotechnology products from the experimental level to the commercial level. Consequently, only if chemical engineering technology is integrated with biotechnology can commercialized biotechnology products be practical.

Because of the lack of professionals with interdisciplinary knowledge in engineering and biotechnology at present in Taiwan, Yuan Ze University has developed a Biomaterial Technology curriculum. The main goal of this program is to help engineering students to better understand the concepts of biotechnology, and to teach them the essential skills of interdisciplinary studies. Generally speaking, the conventional approach is to add a standard biology course, and many schools do offer biology courses at different levels.\(^6,7\) Training in bioengineering can extend outside of the classroom.

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Jia-chi Liang is an assistant professor of the Center for Teacher Education at Yuan Ze University in Taiwan. She received her B.S. and M.S. degrees from National Taiwan University and her Ph.D. from the University of Texas in Austin. Her research interests include curriculum development, science education, and teacher education.

Shieh-shiu Kung is an assistant professor of the Graduate School of Biotechnology and Bioengineering at Yuan Ze University in Taiwan. He received his M.S. and Ph.D. degrees from National Tsing Hua University. His research interests include microbiology, biochemistry, and genetic engineering.

Yi-ming Sun is a professor in the Department of Chemical Engineering and Materials Science at Yuan Ze University in Taiwan. He received his B.S. from National Taiwan University and his Ph.D. from the University of Cincinnati. His research interests include membrane separation, controlled drug delivery, diffusion in polymers, and biopolymers.
setting through undergraduate research and internships. Through the evaluation and integration of the school’s resources, Yuan Ze University established and developed a Biomaterial Technology Curriculum. In addition to including basic biology courses, this program offers advanced courses and integrated and consecutive laboratory courses. The program has developed a collaborative approach between industry and university integrating the resources and teachers of the Department of Chemical Engineering and Materials Science with those of the Graduate School of Biotechnology and Bioengineering. The result is a curriculum relevant to Biotechnology, Biochemical Engineering, and Biomaterials for engineering students to cultivate talents and vision for both engineering and biotechnology. This paper will describe the process of designing the program, and will discuss the implementation, impact, and benefits of an integrated and collaborative approach.

DEVELOPING A SPECIFIC CURRICULUM PROGRAM

Background and Framework of the Program

Foreseeing the importance of interdisciplinary knowledge and training in engineering and biotechnology, we identified two choke points to developing the curriculum. The first is that the engineering and biotechnology departments have their own teachers that are difficult to integrate, due to their differences in background and professional knowledge. The second is that engineering students have deficient knowledge of biology because they often have had little or no formal study of life science since junior high. To boost the Biomaterial Technology program and solve these two issues, we made two adjustments. First, to aid the integration of teachers, the school cooperated with the Far Eastern Group’s Industry-University Cooperative Developing Project: The Development and Application of Microorganism Composite High polymer PHAs (Microbial synthetic polymers). This project happens to be a program that incorporates biology, chemical engineering, and materials science. The main purpose of establishing this relationship was to turn the university’s research energy and educational achievement into the motivating force for rapid industry upgrading. As a result, industry knowledge and techniques were introduced and implemented in all core courses and laboratory courses. Through the guidance of the Industry-University Cooperative project, the teaching resources of the engineering and biotechnology departments came together with professors’ research to help the program integrate theory and practical experiences.

Concerning the students, the program developed an appropriate curriculum plan to resolve their deficient knowledge of the life sciences. The plan included two major points. First, the curriculum was divided into basic and advanced courses, and an emphasis was placed on laboratory courses to improve students’ learning and experimentation skills. Second, a teaching assistance Web site became available to advance the breadth and depth of the students’ learning. The Web site encourages students of different backgrounds to exchange and integrate the knowledge they have learned. The aim is to prepare students to undertake their special topic studies (the third step in their curriculum plan), and to be able to participate in the Industry-University Cooperative project. Having such interactive and practical experience teaches students the analytical and application skills needed to resolve the problems that actually occur in the developing process of the biotechnology industry. Courses of the Biomaterial Technology program link the core biotechnology courses with engineering materials and process unit courses to bring the characteristics of engineering material production and its usage into full play in the field of biotechnology. The framework of the program is shown as Figure 1.

Figure 1. Framework of the Biomaterial Engineering program.
Designing Curriculum

Since 2004, this program has gradually introduced and now offers courses for engineering students who are not freshmen. These additions are outlined in Table 1.

In addition, special topic studies and practice in treating a bioengineering technical problem are required. Figure 2 shows the framework of curriculum and learning goals for each phase. Once students have taken the basic courses, they may take advanced courses and laboratory courses. Laboratory courses are offered during summer and winter breaks to maximize the time students have to learn. There is a great difference between the laboratory courses of this program and those offered at other universities. Traditionally, every laboratory course is independent, as is every experiment in a single course. So while students learn the needed techniques, they often find it difficult to understand complete concepts. Yuan Ze University designed the three laboratory courses with an integrative and consecutive approach. For instance, in the basic biotechnology laboratory course, students learn to use strain screening and purification to identify the strain that can produce PHA (polyhydroxyalkanoate). In their biochemical engineering laboratory course, they also learn that this strain can further produce more PHA by the process unit of fermentation. In the biomaterials laboratory course, students learn the characterization of the material’s physical properties and the preparation of the thermal-pressed PHA films. These sequential laboratory courses not only train students to develop experimental skills, but also build an integrative concept of the origin, production, and application of PHA materials, and help them to apply these concepts in the design of actual experiments.

The college of engineering confers the diploma of the curriculum to the students after they have completed 22 credit hours of courses, including 1 credit hour of special topic studies. After they finish the program, students are expected to have a complete understanding of biotechnology, and be able to combine the present courses of the college of engineering, like unit operation, reactor engineering, process control, materials science, and polymer science. Their understanding of the concepts to apply materials science and engineering into the biotechnology industry is enhanced.

### Table 1

<table>
<thead>
<tr>
<th>Stage</th>
<th>Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic courses (9 credits at least)</td>
<td>Materials Science (required)</td>
</tr>
<tr>
<td></td>
<td>Applied Biochemistry (required)</td>
</tr>
<tr>
<td></td>
<td>Industrial Microbiology (elective)</td>
</tr>
<tr>
<td></td>
<td>Basic Biotechnology (elective)</td>
</tr>
<tr>
<td>Laboratory courses (6 credits at least)</td>
<td>Basic Biotechnology Laboratory (required)</td>
</tr>
<tr>
<td></td>
<td>Biochemical Engineering Laboratory (elective)</td>
</tr>
<tr>
<td></td>
<td>Biomaterials Laboratory (elective)</td>
</tr>
<tr>
<td>Advanced courses (6 credits at least)</td>
<td>Biomaterials (elective)</td>
</tr>
<tr>
<td></td>
<td>Biochemical Engineering (elective)</td>
</tr>
<tr>
<td></td>
<td>Genes and Protein Engineering (elective)</td>
</tr>
<tr>
<td></td>
<td>Biomedical Materials (elective)</td>
</tr>
</tbody>
</table>

**Figure 2.** Framework of the curriculum.

### Evaluating the Effect of the Curriculum

At the start of development of this program, all lecture teachers discussed the goals for the curriculum, the available resources of schools, students’ interests and qualities, and the results of the curriculum, such as the changes in students’ cognition, skills, and attitudes after the curriculum. Evaluation tools in the form of questionnaires were developed to acquire feedback from advisors of students doing special topic studies, and semi-structured interviews were implemented to acquire feedback from students about the laboratory curriculum and industry visits.

**Laboratory Courses**

From laboratory courses, most students report that they learned much and acquired detailed experi-
Students paid attention to the process and the function of chemicals they use in experiments, as opposed to simply following the handbook like before. In traditional engineering experiments, students have little chance to face and resolve unpredictable results. Most students think the biology and engineering models are different. More specifically, the program makes students think of the possibilities and the difficulties of interdisciplinary co-operation.

- “I learned many concepts and skills about operating biology experiments from the courses. These experiments are continuous and integrative; in spite of my insufficient experience, which caused some abortive data and the elongation of time, the teachers and tutors helped me correct me as soon as possible. From conducting these experiments, I have found improvements in my concentration, observations, discussions, and interpretations about the data.”

- “In the two weeks, except for sleeping, we have been working on the experiments almost the time. I dare not to say that I could absorb everything this course tries to teach us, but after sequential learnings, I acquired a more complete conception. I’ve set up the foundation, and now the only thing to do is to build it up. I believe all the hard work would never go down the drain, for we all have learned something indeed.”

- “This is a very interesting laboratory course because we can see different things when applying biotechnology into the field of engineering. Although it is exhausting, we could really learn a lot more new knowledge. Thanks to the teachers, I hope there is another chance to take relevant laboratory courses.”

Courses of the Biomaterial Technology program link the core biotechnology courses with engineering materials and process unit courses to bring the characteristics of engineering material production and its usage into full play in the field of biotechnology.

The students’ positive feedback encourages the teachers to run the program more energetically. Students commenting about the experimental courses mentioned that the arrangements of time was too compact; that they could not understand some terminology; that there were too many groups, or devices were insufficient; and that the contents of handouts were oversimplified. Based on these suggestions the program will be adjusted, so teaching materials and the pace of classes will be modified to focus more on quality than quantity. Other adjustments include collecting and annotating common terminology from all courses; making references available to students in both Chinese and English; providing more equipment and tutors; and sizing-down student work groups.

Special Topic Studies

This program also created a questionnaire evaluating student performance on special topic studies.

The dimensions of the questionnaire refer to the accredited standard of the Institute of Engineering Education in Taiwan. The evaluation mainly concerns the students’ ability to apply knowledge, formulate and execute experiments, use experimental skills and tools, design the process of the experiment, communicate and cooperate within a group, and analyze and solve problems. Aside from the six accredited standards of the department, the program further assesses students’ learning attitude and other abilities, such as reading, writing, interpreting data, and logical thinking. The following are the analyses of the advising professors.

1. **Essential knowledge:** Most of the students doing special topic studies have a clear concept of chemistry, while half have a clear understanding of chemical engineering. Most students also have some understanding of biotechnology and life science, but it is clear that it is difficult for them to build up this knowledge in a short period of time.

2. **Ability to formulate experiments:** Most students can systematically formulate experiments, and are able to correct mistakes they made during the process of the experiment.

3. **Experimental skills and ability to use tools:** On the whole, professors are satisfied with the students’ experi-
visiting activities and speeches related to biotechnology and materials science.

1. Visiting Food Industry Research Institute: The focal point is to introduce the foundation of a strains bank and to teach students the importance of a strains bank to the microbiology industry. Students also see the fermentation pilot plant to see engineering technology applied in the biotechnology industry. The last point is to introduce a range of developing research programs in the institute.

2. Visiting the Industrial Technology Research Institute: The goal is for students to understand the developing programs of the Biomedical Materials of the Biomedical Laboratory and the herbal experimental pilot plant. Students learn how the biotechnology industry develops with consideration to engineering and social demands.

3. Visiting the preparation room of the National Museum of Natural Science and the excavation site of the Hue Lai monument: This visit acquainted students with the approaches and concept of basic Life Science and Anthropology. The researchers of the National Museum of Natural Science also show materials for repairing the preparations of paleontology and excavations and make a description of the merits and flaws of the materials.

4. Speeches: Every year there are a few speeches held by the Graduate School of Biotechnology & Biotechnology; most of them focus on biomaterials, thesis writing, genetic therapy, and the biotechnology industry. These events allow an open discussion between teachers, students, and the speakers, and all speeches are incorporated into the teaching assistance Web site, so teachers can have more detailed discussions with students afterward.

The following feedback from students concerns visiting activities.

- “I hope to visit some industries that connect to the things students will do after graduation. In addition to understanding the industry, we should also understand what areas we can specialize in so that we can make up or take the relevant courses. For example, the AU Optronics Corp., which we visited for the course of chemical engineering, gave me a stirring emotion because we got in touch with the real industry where maybe we’ll work after college. After having discussions with the company, I realized what kinds of talents they really need, and, if I want to work there, what abilities I still lack. I think it is more important that the discussions with industry professionals will help us students plan our futures.”

According to these student interviews, students are very interested in visiting different industries because they can further understand how the knowledge they acquired from books can be put in use. Many students also mention which industries they would want to visit, including TaiYen Biotechnology, pharmaceutical plants, or industries that ameliorate agricultural products. Arrangements for such visiting industries are made each semester with consideration of students’ suggestions.

CONCLUSION

Yuan Ze University’s interdisciplinary program delivers courses of materials science, applied biochemistry, basic biotechnology, industrial microbiology, basic biotechnology laboratory, biochemical engineering, biochemical engineering laboratory, biomaterials, and biomaterials laboratory, and
has succeeded in graduating 24 students from the college of engineering since the first year of the program. Because of the teachers’ diligence in recruiting students, the number of students has increased from 24 to 40. Student evaluations of the program were obtained in 2005 and 2006. More than 90 percent of the students strongly agreed or agreed that the program objectives were satisfied. Also, 66% of the first-year graduates chose to pursue a higher degree or to work in the biotechnology field. These achievements indicate that the goal of this program has been reached. There are four chief reasons compelling students to participate in this program. First, the laboratory courses provide a different experience from other universities. Second, the threshold of the field of laboratory for special topic studies, advisors are most satisfied include disquisitions from professionals, presentation of students’ reading documents, consulting documents, and writing workshops. Finally, graduates emphasized that joining this program acquainted them with the biotechnology industry, and allowed them to assess whether or not they want to pursue more in relevant fields. Therefore, this kind of program offers engineering students more career options, and also extends their vision about technology integration.

The evaluation of the program indicated that what was most attractive to the professors was the students’ studious attitudes and the retention rate in biotechnology and related fields. In the laboratory for special topic studies, advisors are most satisfied with the students’ proactive attitudes toward research; while most students are already overloaded with more than 22 credits, they are still able to demonstrate high motivation and keen interest. Advisors are satisfied with the students’ experimental skills and the operation of valuable devices. Regarding their cognition performance, most but not all students have a clear conception about Biotechnology and Life Science, which indicates that it is not a simple task to build up this knowledge system in such a short period of time.

On the whole, professors and students recognize the value of the program and the importance of coherent training. Through the interdisciplinary program, students have many opportunities to learn about biotechnology directly, which engineering students in a traditional program do not have. More specifically, the program allows the students to rethink biotechnology from different fields, and encourages them to apply what they have learned in engineering to extend their vision. This interdisciplinary cooperation among faculty and institutions has affirmed that having an environment where students and faculty value each other’s contribution is crucial to a holistic education. Through the guidance of the Industry-University Cooperative project, the university’s engineering and biotechnology research and teaching resources are integrated to form a program that combines theory with practical application. This kind of executive approach offers a mutually beneficial model that other universities could imitate.

ACKNOWLEDGMENT

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The expansion of distance learning has created new technologies that distribute educational content, and many online classes are taught using video technology. As schools began using video lectures, however, universities discovered distance learners rated teacher quality lower than traditional students who took the course by sitting in the classroom. Toto studied the use of screencasts, to supplement a first-semester, general chemistry class for distance learners. He identified topics from homework assignments on which students did poorly the year before and then created 60 screencasts that specifically addressed the difficult concepts. When he compared performance between the classes with and without the screencasts, he found that students with access to the screencasts scored 11% better in the course overall and 22% better on the concepts on which prior students scored poorly. Additionally, the students liked the screencasts. For one chapter of the text, Toto did not provide screencasts, and when he later polled students who had used screencasts, 90% said they would have liked to have had them for that chapter.

Screencasts of example problems can be superior to written solutions because students can listen to the instructors explain the problem-solving strategies that they use. Research has shown that when given just the final written solution to a problem, good students use the solutions differently than poor students. The good students use the solutions to justify the individual steps in the solution to gain a deeper understanding, whereas the poor students tend to just follow the steps without understanding.

John L. Falconer is the Mel and Virginia Clark Professor of Chemical and Biological Engineering and a President’s Teaching Scholar at the University of Colorado. He teaches thermodynamics and kinetics courses and incorporates active learning techniques such as ConceptTests and clickers. His current research is in the areas of zeolite membranes and heterogeneous catalysis.

Janet deGrazia is a senior instructor in the Chemical and Biological Engineering Department at the University of Colorado. She teaches a number of the courses in the department including a course on technology for non-engineers. As chair of the Undergraduate Committee, her interests lie in curricular innovations and the use of technology in education. She received her Ph.D. from the University of Colorado in chemical engineering.

Will Medlin is the Patten Assistant Professor of Chemical and Biological Engineering and the ConocoPhillips Faculty Fellow at the University of Colorado. He teaches courses in kinetics, thermodynamics, and material and energy balances. His research interests are in the area of surface science and heterogeneous catalysis.

Michael Holmberg is a program assistant at the University of Colorado. He received a B.S. in chemical engineering in 2008 from the University of Colorado and now works to improve the undergraduate chemical engineering curriculum.

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connecting the solution to the concepts. With screencasts, all of the students are able to hear an expert’s explanation and understand how each step in the solution relates to the underlying principles.

Research into science education has shown that the use of active learning and peer instruction improves student understanding. One effective way to make lecture more interactive is to ask students multiple-choice conceptual questions called ConcepTests during class, have students first answer the questions on their own, and then have them discuss their answer with a group of students. The use of ConcepTests is effective because they allow students to formulate their own ideas, explain their thoughts to their classmates, and get immediate feedback from the instructor on difficult concepts or misconceptions they have during lecture. This method of teaching increases student understanding, but it reduces the amount of lecture time, and students must learn material through reading assignments and problem sets. Students like this interactive approach, but feedback on end-of-course assessments indicates that some students would still like to see the presentation of examples problems “worked all the way to the end.” Screencasts are easily developed and integrated into a course to meet the different learning styles of students. Screencasts also create a different, more individualized, type of active learning experience: A student can work through an example problem at his/her own pace with the screencast paused, and then refer to the explanation when he/she becomes “stuck.”

TYPES OF SCREENCASTS

Short screencasts were used in Fall 2008 and Spring 2009 to supplement five courses: graduate reaction engineering, junior-level thermodynamics, freshmen general chemistry for engineers, the sophomore-level material and energy balances, and creative technology (a freshman-level course for nonengineers). Screencasts were produced using a tablet PC, Microsoft PowerPoint or Windows Journal (software that is included with the tablet PC), and Camtasia Studio screencasting software. The screencasts were typically 5-15 minutes long, and included the following types of presentations:

- **Example problems worked out in detail:** These are similar to example problems that might be worked through during class.
- **Mini-lectures:** Explanations of important topics, similar to what could be presented in class.
- **Clarification of ConcepTests from class:** More-detailed explanations of conceptual problems posed during class or solutions to additional ConcepTests.
- **Clarifications on homework problems:** Multiple students often come to office hours with the same question about a problem, and a screencast can be used to explain the issue instead of explaining it multiple times during office hours.
- **Explanations on how to use new software:** Step-by-step use of menus, how to do certain types of calculations, and what settings are needed.

Screencasts cannot be represented well on a printed page; they are a much more dynamic and visual way to present material than just text. To get a better idea of what screencasts for chemical engineering courses are like, links to some of our screencasts are available at [http://www.colorado.edu/cheme/undergrad/innovative_teaching.html](http://www.colorado.edu/cheme/undergrad/innovative_teaching.html).

PREPARING AND USING SCREENCASTS

Screencasts have a number of potential advantages. Going through the details of a problem solution is probably not the most effective use of class time; more-active learning approaches better engage students in the material. The screencasts are often quite similar to what could be presented in class, but students can go through them at their own pace. This means that they can pause the video to work through calculations on their own, replay sections that were difficult to understand, or watch the video weeks later to review the material. The time it takes to create a screencast is short; producing an example problem essentially takes the same amount of time that it would to work through the solution. Additionally, screencasts of example problems or derivations have advantages over in-class presentations because a Tablet PC screen has much higher contrast than a blackboard, and students do not have to try to quickly copy down all the steps. Instead, they can focus on understanding the underlying concepts.

Screencasts can be integrated into class in several ways. Faculty can refer students to specific screencasts that explain, perhaps in a different way, the same concept discussed in class. Screencasts made by someone other than the instructor can be useful for demonstrating how other experts approach the same problem. The setup of example problems or derivations can be discussed in class, and screencasts can show the complete solutions.

Screencast use can be monitored on a classroom management system like Blackboard. This system records the total number of views, the number of different students who have viewed a file, and the amount of time students spent watching a screencast. Additionally, verbal feedback solicited at the beginning of class or feedback collected via Blackboard can provide feedback on the value of a specific screencast, and can also motivate other students to watch the screencasts.

The investment in money and time to purchase and learn to use the equipment and software is modest: $1,500 or less for a Tablet PC, $300 for Camtasia Studio, less than $50 for a microphone, and perhaps an hour to learn the software. TechSmith’s Camtasia Studio was the best of several types of screen capture programs that we evaluated. Editing is straightforward and the screencasts created by Camtasia can be stored...
It is important to note that the screencasts do not have to be professional quality; they can be the same quality as an in-class presentation of the same material.

in a number of formats. We created screencasts in the Shockwave flash format (.swf suffix) for use on screencast.com or on the University of Colorado’s version of Blackboard because these files seem to work the best with Internet Explorer. We also created files in the Quicktime format (.mp4) so that the videos can eventually be integrated into Apple’s iTunesU. The files are not too large (less than 9 Mb for 10 minutes) and can be played from a Web browser. A PDF version of the file created by Windows Journal software or PowerPoint can also be created and posted along with the screencast so that students can have a printout of what appears on the screen.

It is important to note that the screencasts do not have to be professional quality; they can be the same quality as an in-class presentation of the same material. They can also be generated by graduate students or senior undergraduates. To keep screencasts to a reasonable length, the screen capture program can be paused as information is written on the Tablet screen and then started again to explain what was written. Videos between 5 and 15 minutes seem to be a good length.

STUDENT FEEDBACK

The screencasts in Fall 2008 and Spring 2009 were initial efforts to determine whether students would use them or like them and to establish how to make them. Anonymous feedback and data on screencast use were collected at the end of the semester from the students in these classes. Table 1 summarizes data on the use of screencasts in the graduate kinetics course, screencasts mainly covered material in the first half of the class, and in the thermodynamics class screencasts were only used in the last third of the class.

In anonymous, open-ended feedback about the course collected at the end of the semester, many students freely mentioned how helpful the videos were. Some student comments about the screencasts follow.

- “Screencasts are fantastic. I watched some of them twice.”
- “I learned a lot from the videos. It’s hard learning at such a rapid pace in class, so it’s really nice to be able to rewind and replay the videos as many times as needed.”
- “I liked how the lectures were loaded full of clicker questions. That is really the best way for me to study . . . . The other thing that I really learn best from is videos. I wish you would have made a video for the harder clicker questions for each week.”
- “I like the screencasts; it helps to have the solutions walked through step-by-step with explanation. They are also a great study tool in my opinion.”
- “I love screencasts! I am able to work out the problem at my own pace, and watch the screencast whenever I get stuck.”
- “I didn’t learn as much when we stopped using screencasts.”
- “It would have been valuable to have more example problems worked out.”

SUMMARY

Screencasts are easy to prepare on a Tablet PC and are valuable additions to graduate courses, core undergraduate courses, and a general science course. They are effective supplements to in-class active learning techniques such as ConcepTests. They are relatively inexpensive to create, and production time is minimal. They can be used in various ways, including example problems worked out in detail, mini-lectures, clarification of ConcepTests from class, clarifications of homework problems, and instructions on how to use new software. The feedback from students in the five courses where the screencasts were piloted was overwhelmingly positive, with a significant number of the students freely mentioning how valuable they were to their learning process.

| TABLE 1 |
| Student Feedback On Usefulness Of Screencasts In Five Courses |
| Number of students |
| Course Name | Course Enrollment | Usefull/ Very Useful | Not Useful | Did Not Use |
| Graduate Reaction Kinetics | 47 | 43 | 2 | 2 |
| Junior Thermodynamics | 73 | 29 | 1 | 43 |
| General Chemistry | 390 | 369 | 2 | 19 |
| Sophomore Material and Energy Balances | 52 | 43 | 0 | 9 |
| Creative Technology | 360 | 331 | 16 | 13 |
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REFERENCES

Is There Room in the Graduate Curriculum to Learn HOW TO BE A GRAD STUDENT? An Approach Using a Graduate-Level Biochemical Engineering Course

MARC G. AUCOIN
University of Waterloo • Waterloo, Ontario, Canada

MARIO JOLICOEUR
École Polytechnique de Montréal • Montréal, Québec, Canada

How different is graduate education from undergraduate education? At the course level, the topics become more interesting and focused, and the problems become more challenging and time consuming. These differences aside, however, most graduate courses are very similar to those taken at the undergraduate level. For thesis-driven graduate programs, course work represents only a small portion of the degree sought, especially if one considers that courses are not compulsory in many institutions. Undergraduates may not always understand this aspect of graduate studies and therefore, the fact that the majority of learning at the graduate level must be achieved through self-discovery may be somewhat foreign to most students starting their graduate degrees. Furthermore, graduate training should prepare students to spearhead and carry out a research project, a skill that may or may not be developed at the undergraduate level.

To facilitate this goal, a number of institutions, including the École Polytechnique de Montréal (herein referred to as EPM), have added a mandatory research methodologies course in the graduate curriculum. At EPM this is offered as a general engineering course to all graduate students, regardless of the discipline of study (ING6900 – Méthodes de recherche). At the University of Waterloo (herein referred to as UW), such a formal course is still lacking and it remains up to the thesis advisor to provide this training to his or her students. Although such a course (ING6900) adds to the overall development of the graduate student, the methodology course focuses only on how to perform an efficient literature review and assists the student in writing a condensed research proposal. It thus lacks the applied nature of experimental research and, because of the general nature of the course, does not guide the student on how to go from identifying research hypotheses and objectives based on the state of the art to developing a proper research plan.

It has long been recognized that didactic aspects of courses have a positive effect on student comprehension. Despite this, there are few, if any, graduate lab courses at EPM and none at UW. It almost seems obvious that laboratory-based courses would be extremely valuable to graduate students.

Marc G. Aucoin is an assistant professor of chemical engineering at the University of Waterloo with a current interest in viral vector and virus-like particle engineering. He received his B.A.Sc. and M.A.Sc. in chemical engineering from the University of Waterloo. He received his Ph.D. from the École Polytechnique de Montréal in chemical engineering while conducting his research at the Biotechnology Research Institute of the National Research Council of Canada. During his doctoral studies, Prof. Aucoin was involved with GCH6301/02 as a student in the vintage class of 2004, and then as a teaching assistant and lecturer in 2006.

Mario Jolicoeur is a professor of chemical engineering at the École Polytechnique de Montréal and holds a Canada Research Chair on the Development of Metabolic Engineering Tools. He obtained his B.A.Sc., M.A.Sc., and Ph.D. in chemical engineering from the École Polytechnique de Montréal. Prof. Jolicoeur initiated GCH6301/02 in 2000 and has successfully trained 45 of students with this approach to date.
because of the importance of validating hypotheses experimentally at the graduate level. When preparing a graduate course, it is often desirable to design it in such a way as to tailor it to the specific size and ability of the class so that at least a minimum set of requirements are met by the end of the session. Graduate courses are special in that as little as one person or as many as a couple of dozen students may be taking the course at a given time; therefore it is possible to narrow the scope of material taught, and to explore these more thoroughly. An open-ended laboratory course is well suited for obtaining this flexibility.

The following describes a course that addresses many of the aforementioned issues while maintaining its identity as a graduate course on cell culture and modeling. Chemical engineering has seen an increasing presence of biology in the curricula, especially at the undergraduate level, a trend that is also being observed at EPM and UW. A course such as this, therefore, serves multiple purposes: to deepen and continue education in bioprocess engineering while providing a means for students to transition from an undergraduate to a graduate mindset. The course in its present form has been offered in the department of chemical engineering at EPM since 2004 and has integrated a number of concepts aimed at enabling students to first understand their role in research and then become better researchers. To achieve this, the course has amalgamated concepts also described by others with a focus on the implementation of experiments proposed in a research plan.

OVERVIEW OF THE COURSE

The course is listed in the EPM graduate calendar as GCH6301/02 – Biosystems Engineering/Cell Culture – Cell Culture and modeling (Ingénierie des biosystèmes/Culture des cellules – Culture cellulaire et modélisation). It is meant to be a hands-on course working with a bioreactor and the cultivation of a microorganism, often E. coli, which is an obvious choice as a model system given the shortened study period and the costs associated with the implementation of experiments. This course poses an open-ended question without a defined problem. The students are asked to identify the current limitations that exist in a particular field, such as the production of protein in E. coli, evaluate the needs of the state of the art, and decide a course of action that is plausible given the somewhat limited resources available in a course setting. The choice of microorganism is dependent on the availability; in the past, students have benefitted from the close ties between EPM and the Biotechnology Research Institute of the National Research Council of Canada (Montréal, Québec, Canada), which has supplied various recombinant microorganisms for study.

This course satisfies one of the five courses required for thesis-based master’s and Ph.D. degrees at the EPM; however, this course is not mandatory. It is operated as a scaled-down research project run intensively for 5-6 weeks. Students are expected to dedicate all the time defined by the credits awarded for this course: 3 credits = 135 hrs or up to 27 hrs per week. The course, therefore, requires that the students be dedicated only to this course while it is being given. The students gain insight, however, into the type of research that can be conducted at the graduate level and gain a better understanding of the processes involved in a research-based graduate degree. This course also illustrates how training for a research-based graduate degree can be completed in a little over a month: from problem synthesis, statement of hypothesis and objectives, implementation and analysis of experiments, as well as defense of their work.

This course can be done with as little as three students; however, we feel that this is not an optimal size given the resources required in terms of teaching assistants discussed further on. Optimally, this course would be given to a group of between eight and 16 students, allowing the instructor to create groups of three to four students initially, with the possibility of combining groups as the course progresses.

Currently this course is given in the Spring term (May–June). Certain graduate students—especially those exiting their bachelor’s degree from EPM and UW—start at this time, which makes the placement of this course ideal, since it can then be taken in the first term of study. Students starting in the Fall or Winter terms would only get the opportunity to take this course in their second or third term, which is still early enough to benefit the student. Although it may be theoretically feasible to place this course in another term, there are a number of practical reasons that do not allow this course to be shifted to another semester, including the use of this laboratory for undergraduate teaching in Fall and Winter terms.

GENERAL OBJECTIVE

The general objective of this course is to transform the student from having an undergraduate mindset, which looks to textbooks for solutions, to a graduate mindset, which understands that textbook information is meant as a comprehensive review of the literature at an earlier point in time. Students are taught to understand that specifics and the state of the art are found in scientific peer-reviewed journal articles. This change in mindset aims to drive the students to question results or approaches that have led to earlier conclusions, and gain an appreciation for the overall scientific method.

A second aspect that is highlighted in this course is the difference between report writing and scientific communication. Not all schools permit “theses” by scientific publication; however a number of schools do. The benefit of such a format is that it maximizes the potential for good scientific work to reach the masses, with the drawback being that these types of theses do not necessarily read as well as conventional theses. With traditional theses, however, professors may lack detail or...
complete understanding of the student's work described in the thesis if the original author/student is incommunicado, which may happen more often than not, if the author has moved on and is working in industry and becomes overwhelmed with commitments that were not necessarily pre-existent while in academia. The ability to write a scientific publication is also of high importance. This is why the course emphasizes the preparation of a scientific manuscript at the end. It is often surprising that even though a student normally reads hundreds of papers and book chapters during their graduate degree, students often have difficulty writing a manuscript that has coherent structure and argumentation, a skill often lacking of engineering undergraduate students.

SPECIFIC OBJECTIVES

To achieve the global objective of the course, students are required to assimilate the accumulated literature in a specific field; develop, based on a scientific approach, a strategy to produce protein in a bioreactor; carry out the strategy in the lab; and validate the results. This approach results in general theoretical and practical knowledge that will permit the student to understand, prepare, operate, and optimize a bioprocess. More precisely, the student that takes this course develops an ability to: 1) understand the notion of aseptic techniques and learn how to apply them; 2) apply a scientific methodology to the study of cell culture/fermentation; 3) describe, explain, and model cellular phenomena; 4) operate a pilot-scale bioreactor; 5) learn how to determine bioprocess parameters that can be optimized; and 6) learn how to write and defend a scientific manuscript.

PREREQUISITES

This course involves intensive cell culture in a laboratory setting. A good foundation in biochemical engineering is needed and knowledge of biochemistry and cellular biology are assets, but are not necessary. General chemical engineering skills such as the ability to develop mass balances around a system, in this case around a bioreactor, are essential. Working knowledge of a computer coding language such as MATLAB, that will allow the simulation of the process, is also required.

Most chemical engineering undergraduates that have attempted this course have the pre-requisite skills upon entry into the graduate program; however, it becomes fairly obvious within the first couple of lectures whether or not a student has the required skills to take on this course and it becomes the responsibility of the instructor to discuss the situation with the student. In the past, we have had to ask students to withdraw from the class. Although we believe that this course has many general lessons that are important for graduate students, it is meant to be a graduate-level course in biochemical engineering. As such, although the lessons to be learned about graduate studies may be lessened if the student takes this course beyond their first year as a graduate student, the student will still benefit from taking an advanced biochemical engineering course.

COURSE SYNOPSIS

Using a heuristic approach, the principal problems encountered with in vitro cell culture are studied. The students are called upon to work together in teams to develop their knowledge in this field. Students survey the literature in a short period of time, present a summary of the literature highlighting what has been accomplished and at the same time identify areas that could benefit from further exploration. In consultation with the professor and the teaching assistant, the students assess what type of experimentation is feasible in light of the available resources; plan a course of action; perform a predetermined number of experiments that build upon previous work; analyze the data; choose a scientific journal appropriate for the work done; and write a scientific publication for that journal. Once the article is written, the project needs to be defended in front of a panel consisting of the professor and the teaching assistant(s). Figure 1 describes in more detail the general operation of the course since 2004.

REFERENCE MATERIAL AND AIDS

Several textbooks are recommended as complementary to the course[14–18] and can span different levels of experience depending on the strength of the class. All of the documents and class notes of an undergraduate course on Biochemical Engineering (GCH4650) are also made available to the students.

Lectures

During the first week, a seminar/lecture component is given to provide insight on the system to be studied. This includes major elements of biochemical/bioprocess engineering and relevant background information, for example characteristics of the microbial strain to be used. Practical and theoretical information is given based on need, which allows the course to be tailored to the directions the students want to take, while at the same time meeting the learning objectives set for the course.

Meetings/Discussion Groups

Frequent meetings are scheduled between the students and the teaching group. During these meetings, students are evaluated individually and in a group depending on their progress. Two formal presentations are required by the students to assess progress achieved in the course. Other meetings are scheduled on a daily basis to assist students in their reflections.

Teaching Assistants

Given that the maximum class size is approximately 15, justifying more than one teaching assistant is quite hard; yet, this course is highly dependent on the teaching assistant(s). Teaching assistants are a major resource for the students taking
Week 1
- Presentation of objectives and organization of the course.
- Introduction to equipment used in cell culture:
  - Cell needs vs. what a bioreactor can offer
- Distribution of the case study.
- Distribution of previous year’s final report.
- The students present a critique of last year’s final report.
- The teaching group presents last year’s corrected report.

Week 2
- Students present a literature review
  - The bioreactor is characterized experimentally in terms of:
    - Sterility
    - Hydrodynamics and mixing
    - Mass transfer
    - Shear stress
- Students define their experimental strategy in order to ensure that the cell needs are met by the bioreactor and culture strategy.

Week 3
- The teaching group remains available to the students.
- Students present data and their analysis from bioreactor characterization studies.
- Students define their culture strategy.
- Students perform bioreactor cultures, sample and data analysis.

Week 4 to 6
- The teaching group remains available to the students.
- Students may perform a second series of cultures to confirm specific findings.
- Students analyze the data collected and write a final report.
- Students defend orally their report on the last Thursday of the course.
- The final report is submitted to the teaching group, with revisions from the oral defense, on the last Friday of the course.

Acquired knowledge
- Understanding of cell needs when cultured in vitro.
- Overview and selection of bioreactor configuration.

Acquired skills
- Identification of appropriate bioreactor given cell type.
- Critical evaluation of literature.

Acquired knowledge
- Understanding of how to characterize bioreactor behavior experimentally.
- Understanding of how probes can be used to assess bioreactor operation.

Acquired skills
- Development of experiments required to identify an appropriate bioreactor for a specific organism.
- Competency in detecting whether a bioreactor or probe is performing adequately.

Acquired knowledge
- Behavior of cells in a bioreactor.
- Behavior of bioreactor during a culture.
- Basic analytical techniques.
- Development of appropriate experimental design.

Acquired skills
- Preparation, operation and sampling of a bioreactor culture.
- Critical assessment of experimental data.

Acquired knowledge
- Techniques for modelling cell culture.

Acquired skills
- Analysis of culture and process data.
- Situation of experimental data with respect to published literature.
- Drafting a manuscript.

Figure 1. General operation of GCH6301/02 since 2004.
the course. Although they may not be present at all times during the periods of experimentation, the teaching assistant(s) are essentially “on-call” for the students. If the teaching assistant does not have an existing relationship with the instructor, whether this is an advisor-student or mentor-protégé relationship, the assistantship task may be viewed as being overly demanding. In the past, however, the assistantship position has also served as a learning experience and in a way follows a recent Teaching Tip, which describes the benefits of informally sharing a course with a graduate student.

Over the years this course has been taught, several students who have taken this course have also moved on to become TAs and lecturers for the course. The importance of this circle should not be lost, as it fulfills many aspects of graduate education and is at the heart of the success of this course. Although this relationship has remained informal, this aspect of the course is similar to the mentorship programs suggested by others.

Not all students that have taken the course have the aptitude to take on such a teaching task, however. This assistantship requires a person that is flexible, approachable, resourceful, and able to think quickly.

STUDENT EVALUATION

Every student starts out with a grade of A or excellent. After each meeting, the students’ grade is subject to change to A (excellent), B (satisfactory), or F (fail). The grades can be individualized by attributing the grade based on the level of progress on the sub-objectives they have set for themselves or that were set for them in previous meetings. For example, if a student within a group has agreed to prepare a statistical design of experiments, to assess certain conditions with the least number of experimental runs then at the following meeting, this student would be individually assessed against this sub-objective. Furthermore, this student would also be graded within the context of the group for cohesion of that sub-objective with the ones set by the other members of the group. The evaluation process, therefore, assesses their progress within the group and allows for the individualization of grades. This evaluation is done by both the instructor and the teaching assistants individually, and following a discussion between the teaching staff, a final mark is given. The marking scheme of A/B/F was chosen because at EPM, the Ph.D. program requires students to maintain a minimum of a “B” in each course to stay in the program, and an overall average of “B” in the master’s program.

The second portion of the student’s mark is based on a final report in the form of a scientific manuscript. The group marks and the individual marks are combined to yield the student’s final mark. Fifty percent of the grade is awarded for the term performance (25% for their individual contribution and 25% for the advancement of the group) and 50% for the final manuscript (which is a group mark). As can be seen, there is a significant weight associated to group work in this course.

This course, from an evaluation perspective, is also of benefit to professors who are looking to assess a student’s potential as a graduate student; it allows the professor to evaluate the student’s abilities: from their thought process to their critical thinking and reasoning skills. Given that this course is generally taken before the fourth semester, which is also the deadline for a student to defend their research proposal for their doctoral degree, this may also serve in the future as part of the qualifying exam. In the past, EPM has had topical qualifying exams in Reactor Engineering, Polymer Engineering, or Biochemical Engineering, which have been recently disbanded. This is in line with many other chemical engineering departments that seem to be moving away from course-based qualification processes that emphasize coursework rather than research potential. The course described here could therefore be used as a topical qualification exam to assess research potential.

THE CASE OF GCH6301/02 SUMMER 2004

The pedagogical approach described here was first experimented with in 2004 and resulted in an unexpected level of success that encouraged us to continue in this direction in subsequent years. Summer 2004 brought together six motivated graduate students: four registered in the thesis-based graduate program, (two Ph.D. and two M.A.Sc. candidates), and two registered in the course-based master’s program. Two students were in their first semester, two were in their second, while the others were in their third and fourth terms.

Students were introduced to the production of GFP in E. coli under a temperature-sensitive promoter. The course followed closely the path described in Figure 1. Although the class was first split into two groups of three to assess the state of the art, the six students were combined into a single group for the development of research objectives and experimentation. This was also useful to follow and sample the bioreactor cultures, which were followed for more than 12 consecutive hours (a real industrial context). Teamwork in industry requires that all involved contribute and that a certain amount of confidence between team members exists. Similarly, this relationship must be understood by the graduate students. The Summer 2004 students obviously showed different scientific and technical skill levels, but what made this group stand out was the “chemistry” within the team allowing for very good interaction and communication. As a result, the project report/manuscript was also of high quality. It was also highly interesting to note at the “defense” that every team member was able to answer the questions adequately; showing that every student actively participated in the various aspects of the course including classroom concepts, the laboratory, and writing up the project. Moreover, due to the concepts and methodologies explored by the students, the manuscript submitted for the course was submitted, with a few modifications, to a scientific peer-reviewed journal. It should be noted that alterations to the manuscript did occur after the course.
was actually completed—driven by the students and not the TA or instructor. The instructor, however, remained available to the students for valuable feedback. Communication after completion of the course was done mostly through e-mail. Although initially rejected for publication, the manuscript was revised based on the reviewers’ comments, again driven by motivated students, re-submitted to another journal having a higher impact factor, and was accepted and published.

The manuscripts at these various steps, as well as the reviewers’ comments, have also found their way into later offerings of the course. In Summer 2006, students were also introduced to the production of GFP in E. coli under a temperature-sensitive promoter, still following the chronology described in Figure 1; however, this time the introduction was through the previous year’s report and manuscripts. This allowed the students to become familiar with the system very rapidly, question previous approaches, and situate themselves in the literature by using the reference list in the report. To really make the students gain an appreciation of the work conducted previously, they were asked to review and critique the article produced by the previous year’s class, identify strengths and weaknesses, and highlight ways to push the study further. This served as the first assignment upon which they could be evaluated. To further the students’ experience, the professor and teaching assistant went through these documents, helping the students highlight the strengths and weaknesses in both the scientific and editorial aspects associated with the manuscripts, as geared for a scientific journal. From this process, students were asked to propose what research they would like to perform in order to answer questions that may have arisen from the analysis of the manuscript, so as to better understand the bioprocess and maximize productivity of the system. These activities occurred in the span of two weeks. To further develop their understanding of the system, the students created simulations of the process using MATLAB. Here they were able to modify process parameters and see the effects of various changes. Following this, the students were brought to the laboratory setting and were asked to use pilot-scale equipment to test their hypothesis and determine the predictive capabilities of their kinetic model. Various strategies were used to sustain the production of GFP under the control of a temperature-sensitive promoter, in batch and fed-batch modes of culture.

The final outcome of this course obviously varies each year because of the composition of the group, as well as the “chemistry” between the members. The 2004 group revealed to be a “Grande cuvée” (an appropriate reference to a good year for wine, considering this is a biochemical engineering course). In any case, this approach has been highly stimulating for both the professor and for students taking this graduate course, who now strive to come up with similar advances through this course. Another exciting outcome of this course came from students who decided to switch from the course-based program to the thesis-based program, because of the hands-on aspects of the course.

**COURSE CRITIQUE AND STUDENT FEEDBACK**

Although the course (in name only) has existed since 2000, the approach taken today started in 2004. The course has therefore gone through many changes over the years, evolving as a result of student comments and course evaluations. Every time the course is offered, the students have the opportunity to submit a critique. The marking is on a scale of 0-100%, 100% being complete approval of the course, the content, and how it was taught. On average, the course evaluations have increased significantly—especially when examined against the first offering in the summer of 2000 when it was given as a fully theoretical course, built on the same framework as classical undergraduate courses. In the last few times this course has been offered, it was given the highest rating in all categories assessed in the course critique, a positive sign that this is a valuable learning experience even though it can be quite demanding. The most recent class to take the course unanimously gave it a 100% rating.

The most frequent student comments for pre-2004 offerings pointed to the lack of experimental work. Retrospectively, those that have taken the course more recently regard the high work load as extremely beneficial, concluding that they “have learned a lot in a very short time.” It can be said that this is mostly due to the many resources made available to the students, including the teaching staff.

It has been hard to truly quantify the mid- and long-term effect of the course. All graduate students who had taken the course in 2004 have graduated, except for one student still pursuing a Ph.D. degree (year 4). This 100% (expected) graduation level is very high compared to what is usually seen, however, given the limited number of students, the results may not be statistically significant. Furthermore, given that the instructor assesses the capabilities of the students in the first few classes, we cannot discount that selection may have played a role on the success of the students.

Following the completion of the course, those who continued in a thesis-driven program (M.A.Sc. or Ph.D.) did seem to show a better understanding of research project management, as well as the importance of the existing literature and of critical thinking. These students, we believe, also showed a greater maturity toward research. Unfortunately, these assessments are all subjective. Our one true measure of success has been the continued student involvement after the course was finished, either by future involvement as teaching assistants or by continued efforts on drafting a publishable piece of work.

**CONSTRAINTS, LIMITATIONS, AND FUTURE POTENTIAL**

Timing and budget comprise the major constraints at EPM. This course was developed around infrastructure that was either kindly donated to the department of chemical engineering by the National Research Council of Canada, such as the 20L bioreactor, or that was available from Prof.
Jolicoeur’s laboratory. Much of the department’s equipment is also used for undergraduate training in the Fall and Winter semesters; therefore, the only time this course can be given currently is in the Summer term. Given the time of year that this course is given, it is expected that all students should have the opportunity to take this course before their 5th term, which is approximately the same timing given to complete the requirements of their comprehensive examination. It can therefore provide an additional indicator of the quality of the student, and be used as a practical component of the qualifying exam.

The major expenses for this course remain the cost of hiring teaching assistants. We have been fortunate to have had the constant support of the chair of the department, Prof. Robert Legros. In terms of material, cost is kept at a minimum by culturing bacteria, such as E. coli. As such, the major expenses for running these labs have been the cost associated with purchasing glucose and lactate assay kits.

As we start increasing the complexity of the course, given that we can use what previous classes have done in earlier offerings of the course as a new starting point each time, we may be faced with increasing expenses if we expect to explore novel aspects of the system. Another option may be to widen the focus of the course, for example including control theory to optimize the operation of a reactor. It is our intent to set up a series of variations, bringing in concepts like metabolic engineering, on-line and at-line monitoring and process control, and perhaps develop an advanced course in bio-process control within the control unit at the EPM.

Although this course is currently not a required course for all graduate students, we believe that it can be used in the training of students focused in other areas of chemical engineering. For example, students specializing in mass transfer, heat transfer, or rheology may benefit from taking this course, without having to actually change the content of the course. Extension to these adjoining fields may require additional expertise and buy-in from other faculty members in the department. Widening the focus, however, could pose fresh problems especially in trying to integrate students with varying backgrounds.

CONCLUDING REMARKS

We believe that this type of course is of crucial importance for three reasons: 1) it allows the incorporation of different concepts that should be assimilated by new graduate students and considered as key success factors for their own research project; 2) it allows the development of a productive graduate student, which is why we believe that room should be made in the graduate curriculum to ensure that there is an opportunity, early on, to experience being a graduate student; and lastly 3) this course can serve as an evaluation tool for graduate school potential.

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A TEACHER’S TEACHER

RICHARD M. FELDER
North Carolina State University

One of the giants of engineering education hit a couple of milestones recently. Jim Stice, the Bob R. Dorsey Professor Emeritus in Engineering at the University of Texas at Austin, celebrated his 80th birthday last year, and last June he retired from the ASEE National Effective Teaching Institute, which he co-founded two decades ago. To old-timers in the world of engineering education Jim is legendary, but many youngsters of, say, 60 and below, don’t know who he is or how much he’s done for our profession. I’d like to remedy that deficiency.

A little personal history first. When I was a fresh young assistant professor, like virtually all of my faculty colleagues I had never been taught a thing about teaching before I walked into my first class. Not knowing any better, I did unto my students as my professors had done unto me, mechanically transcribing my lecture notes onto the chalkboard so my students could mechanically transcribe them into their notebooks. (At least they had to stay awake to do that—luckily for them, PowerPoint hadn’t been invented yet.) I went on like that for years, assuming that the glazed eyes and low attendance and abysmal test grades I kept seeing were unavoidable facts of life in engineering.

Then one day I stumbled into a Jim Stice talk at an AIChE conference. In his uniquely droll style, he told us that there were more effective ways to teach than nonstop board stenography, most of which involved engaging students actively and getting them to take more responsibility for their own learning. He also made me aware for the first time that an engineering professor could make teaching and learning the focus of his faculty career at a research university and the sky wouldn’t fall. Those two radical notions became the foundation of the last 25 years of my 40-year academic career. I have had several defining experiences in my life, but none of them had a greater catalytic effect on me than that 20-minute conference presentation.

In the years since then I’ve been lucky enough to collaborate and hang out with Jim and find out how truly remarkable he is. Since most of you who are reading this haven’t had that privilege, let me introduce him to you.

Richard M. Felder is Hoechst Celanese Professor Emeritus of Chemical Engineering at North Carolina State University. He is co-author of Elementary Principles of Chemical Processes (Wiley, 2005) and numerous articles on chemical process engineering and engineering and science education, and regularly presents workshops on effective college teaching at campuses and conferences around the world. Many of his publications can be seen at <www.ncsu.edu/felder-public>.
Jim’s teaching throughout his 43-year active faculty career was exemplary. He always set high standards for his students, routinely posing problems that involved high-level analysis and critical and creative thinking, and challenging his students to do more than they ever imagined they could. Students often rebel against that sort of challenge, but thanks to the clarity of Jim’s explanations and his unique Ozarkian humor, most of the students lucky enough to be in his classes met or exceeded his expectations and loved him. He won a teaching award in his first term at the University of Arkansas and at Texas he won nine more—including one for being the best teacher on the entire campus—along with two awards for excellence in advising.

So far that’s a fairly conventional story, but if there is one thing James E. Stice is not, it is conventional. On his journey from bright young assistant professor to venerable sage, Jim did some groundbreaking things. Here are some of them.

When Jim went to Texas in 1968 at the invitation of Dean John McKetta, it was to create and direct the Bureau of Engineering Teaching, the first center for engineering teaching and learning in the United States and probably the world. It was an idea ahead of its time—so far ahead, in fact, that 40 years later most engineering schools still haven’t figured out that a pedagogically savvy engineering professor is much more likely than a social scientist to persuade engineering professors to change how they teach. One of his landmark contributions as Bureau director was to create the first-ever course on College Teaching for engineering graduate students, a course he taught from 1972 through 1997. Jim had so much success helping his engineering faculty colleagues improve their teaching that UT made him the director of the nation’s first campus-wide Center for Teaching Effectiveness, a position he held for 16 years.

Jim’s list of publications includes 55 articles and two books, but the numbers don’t tell the real story. Several of the articles deal with now-familiar concepts that were virtually unknown in engineering education when Jim introduced them to the rest of us. They include learning objectives and Bloom’s Taxonomy, engineering-specific instructional development, and diverse student learning styles and “teaching around the cycle.” He also wrote landmark papers on computer-based instruction (written years before large-scale implementation of instructional technology became feasible), the lack of correlation between grades in college and professional success, and teaching problem-solving skills. Few engineering professors can match the number of Jim’s education-related publications, and none can match the impact of those publications on the discipline. If he had chosen a different career, engineering education would not be what it is today.

As important as Jim’s publications are, however, his professional development activities arguably constitute his greatest legacy to the profession. He has given hundreds of invited seminars and teaching workshops at conferences and on campuses all over the country, and he co-developed the ASEE National Effective Teaching Institute and co-facilitated it every year from its first offering in 1991 through 2009. Thousands of engineering faculty are better teachers today because of their participation in Jim’s programs, and hundreds of thousands of students have benefited from the improved instruction they received from those participants. Jim’s contributions to education have been honored with a number of national awards, including the ASEE Chester F. Carlson Award for Innovation in Engineering Education and the first ASEE Chemical Engineering Division Lifetime Achievement Award for Pedagogical Scholarship.

Last June at the 2009 Annual ASEE Conference on his home turf in Austin, Jim announced that he would be stepping down as NETI co-director, which is sad news for future participants. They will not have the unique privilege of hearing about the strange and colorful characters who inhabit Jim’s past, like his former roommate who was so thin he could take a shower in a rifle barrel, or the fellow who was so bow-legged he couldn’t trap a hog in a ditch, or his frustrated student who in a particularly bad moment screamed like a mashed owl. I know and love and could recite his words at future NETIs, but they’d just sound silly with a New York accent.

And so I celebrate Jim Stice—my mentor, role model, and dear friend. Jim, Rebecca and I will sorely miss visiting with you and Betty every June, enjoying our ceremonial pre-workshop martinis (yours with Tanqueray and three olives), sitting in the back of the room during your presentations and watching a true master engaged in his craft, having our celebratory post-workshop blowout dinner, and doing a whole lot of laughing for four days. Thanks for all you’ve done for an uncountable number of engineering teachers and students. Thanks for showing me that if your passion is teaching and learning you can also make it your profession. Thanks for all the wisdom, and all the friendship, and all the laughter. Here’s to you!
From Numerical Problem Solving to Model-Based Experimentation—
INCORPORATING COMPUTER-BASED TOOLS OF VARIOUS SCALES
Into the ChE Curriculum

Mordechai Shacham
Ben-Gurion University of the Negev • Beer-Sheva 84105, Israel
Michael B. Cutlip
University of Connecticut • Storrs, CT 06269
Neima Brauner
Tel-Aviv University • Tel-Aviv 69978, Israel

1. INTRODUCTION
Many of the challenges facing chemical engineering departments regarding the use of computers in undergraduate education were recently reviewed by Edgar.[1] These challenges come about because of the substantial growth in the number of multiple-purpose and dedicated software packages used in the chemical industry, education, and research. At the same time, there remain substantial practical and educational benefits to teaching computer programming using languages such as FORTRAN, Visual Basic, C, or C++. There is obviously not enough room in the undergraduate curriculum to include all the courses required to teach computer programming and all the state-of-the-art software packages currently used in chemical engineering. Thus, it is desirable to construct a general framework that enables sufficient coverage of computer programming as well as the use of multiple purpose and dedicated software packages.

This paper is organized as follows. In sections 2 and 3, the current computing needs in academia and the chemical industry are reviewed. In section 4, the content of a suggested introductory course for modeling and computation for chemical engineers is outlined. It is demonstrated that with a proper choice of software packages several computing-related subjects can be combined in a time-efficient manner, enabling the study of the most important skills in a single course. Section 5 discusses a suggested numerical methods course. Finally, section 6 presents a proposed framework for incorporating computational tools of various scales into the ChE curriculum.
The study of computer languages such as Fortran has been included in the ChE curriculum since the 1960s.

years ago. Since then, this field has expanded considerably. Now it includes the study of computer languages, problem solving using numerical and statistical methods, process simulators, computational fluid dynamics (CFD), virtual laboratory experiments, process and product design, and molecular modeling. A more detailed description of some of these issues follows.

2.1 Study of Computer Programming Languages

The study of computer languages such as Fortran has been included in the ChE curriculum since the 1960s. This was enabled by the publication of the book by Lapidus on “Digital Computation for Chemical Engineers,” and textbooks containing Fortran programs, such as Material and Energy Balances by Henley and Rosen and Applied Numerical Methods by Carnahan, et al. Programming languages have been studied in “Computer Science” courses. These have varied over the years and have included Fortran, PL/1, Pascal, C, C++, MATLAB (a registered trademark of The Math Works, Inc.), Excel (a registered trademark of Microsoft Corporation, <http://www.microsoft.com>), Maple (a trademark of Waterloo Maple, Inc., <http://maplesoft.com>), MathCAD, MATLAB, Mathematica (a registered trademark of Wolfram Research, Inc., <http://www.wolfram.com>) and POLYMATH. A comparison of the performance of the various packages in solving the set of 10 problems was reported by Shacham and Cutlip. A textbook demonstrating the use of POLYMATH for numerical solution of problems in various required chemical engineering courses was published by Cutlip and Shacham. Currently there are many textbooks that rely on one or more mathematical software packages to numerically solve the presented problems. (See Edgar for a list of such textbooks).

Most of the problems that are included in the textbooks and the publications mentioned in the previous section can be characterized as Single-Model, Single-Algorithm (SMSA). Typical examples of SMSA type problems include the following:

1. Steady state operation of a tubular reactor, where the model consists of a system of ordinary differential equations and explicit algebraic equations. One numerical integration algorithm (such as the 4th order Runge-Kutta) can be used to solve this model.
2. Calculation of the 3-phase bubble-point temperature for a nonideal liquid mixture, where the model includes a system of implicit and explicit algebraic equations. A nonlinear equation solver algorithm (such as the Newton-Raphson technique) can be used to solve this problem.
3. Fitting the Wagner equation to vapor pressure data using a linear regression algorithm.

These types of problems can be solved efficiently by several software packages, as was shown by Cutlip, et al. Even in undergraduate education, however, there is often a need to solve more complex problems that can be characterized as: Multiple-Model, Single-Algorithm (MMSA), Single-Model, Multiple-Algorithm (SMMA), and Multiple-Model, Multiple Algorithm (MMMA) problems.

A typical example of a MMSA problem is the cyclic operation of a semi-batch bioreactor. The three modes of operation of the bioreactor (initialization, processing, and
2.3 Large-Scale Simulation

Typical claims for large-scale simulators include "they enable black-box modeling" and "it is possible for the students to successfully construct and use models without really understanding the physical phenomena," as noted by Dahm, et al. [13]. Those drawbacks are only relevant, however, when the use of large-scale simulation programs completely replaces numerical problem solving in the curriculum. There are many potential applications for large-scale simulation programs that cannot be carried out by the general-purpose mathematical software packages. Such applications include visualization of flow fields using CFD software, investigation of cause-effect relationships among operational parameters of a particular process, and the simulation of virtual laboratory experiments. Thus, large-scale simulation tools enable students to experience complex systems that may be difficult to attain through direct contact with the equipment itself.

3. COMPUTING IN INDUSTRY

Surveys concerning the use of computer-based tools in the industry were carried out recently by the CACHE Corporation (Edgar [11]) and by Cameron and Ingram [19]. These surveys suggest that engineers and scientists in industry can be separated into two groups: those whose main task is modeling (modelers) and those whose tasks do not include modeling. In the CACHE survey, there was no differentiation between the two groups, while the second survey [19] included only the modelers group. The CACHE survey found that practically all the engineers and scientists in the industry (98%) use spreadsheet programs (the most popular being Excel). Spreadsheet programs are used mainly for data analysis (88%), numerical analysis (47%), material balances (25%), and economic studies (24%). The survey indicated a considerable level of use of database management systems (65%). The level of use of other software tools among the general population of industrial practitioners is much lower, and most of it probably represents their use by the modelers group.

Cameron and Ingram [19] list the tools used by the modelers group according to the extent of their use, as follows: Excel, flow sheeting packages, MATLAB, direct coding, CFD, hybrid modeling, and simulation with optimization programs. Additional tools such as molecular simulation, expert systems, and programs for risk analysis are used to a lesser extent.

4. AN INTRODUCTORY COURSE FOR MODELING AND COMPUTATION FOR CHEMICAL ENGINEERS

A review of the state of the art of computing in academia and in industry has demonstrated that incorporation of the most necessary computing tools into the undergraduate curriculum represents a major challenge. To meet this challenge, it is necessary to provide the students the ability to solve problems of various levels of complexity in a single course.

One possible approach uses the software packages POLYMATH, Excel, and MATLAB in such a course. [30, 21] POLYMATH is an easy-to-learn and user-friendly problem-solving tool, which can be employed in most undergraduate and graduate courses for solving SMSA problems and carrying out various types of regressions with statistical analysis. Excel is included in the introductory computing course because of its widespread use in the industry, suitability for carrying out parametric studies, and connection with programming...
5. A NUMERICAL METHODS COURSE FOR CHEMICAL ENGINEERS

A numerical methods course, which is taught in most, but not all, chemical engineering departments, can considerably enhance the programming and the numerical problem-solving capabilities of the students. The effectiveness of the course can be increased by introducing a set of interesting problems that keep the students engaged. In this section a brief review is presented of the sources of problems and case studies, applicable to chemical, biochemical, and environmental engineering as well as to process safety analysis, which require numerical solution.

A library of SMSA problems involving solution of nonlinear algebraic equation of various levels of difficulty was presented by Shacham, et al. References 9, 12, and 24 through 32 present examples where the mathematical model includes ordinary differential equations (ODE). Most of the problems are of SMSA type, however References 12 and 31 present MMMA examples and Reference 32 presents a two-point boundary value problem, which can be categorized as an SMMA problem. Inadequate error tolerances, use of inappropriate integration algorithms, and careless rounding of model parameter values can lead to erroneous solutions. Examples regarding such situations are presented in References 26 and 30. References 12 and 31 present examples applicable to the biochemical engineering field. Process safety related examples are presented in References 27 and 29. An environmental engineering related example is presented in Reference 28.

An example associated with solution of differential-algebraic equations (DAE) is presented in Reference 33. Various aspects associated with data analysis and regression are demonstrated in References 32 and 34-36. The particular problems demonstrated include examples of collinearity between independent variable, use of inappropriate statistics and plots to assess the quality of the regression model, and the use of insufficient number or redundant regression parameters.

Determination of the number of significant digits used in computations, when rounding the model parameters or in presenting the results, represents a special challenge. Examples associated with these issues are presented in References 23, 26, 30, and 36.

Shacham presents a typical midterm exam that was recently given at the Ben-Gurion University of the Negev in a Mathematical Modeling and Numerical Methods course that involves MATLAB programming. This course is given to third-year ChE students and the duration of the midterm exam is two hours. The exam questions are based on problem 12.3 in the book of Cutlip and Shacham and can be characterized as an SMSA problem. There are two questions in the exam. The first one involves the calculation of the Wilson equation coefficients for a binary system, which includes ethyl alcohol.
and another randomly assigned organic compound. The Wilson equation represents activity coefficients for nonideal systems and in this question the students should use azotropic point data to calculate the coefficients. This requires the solution of a system of two nonlinear algebraic equations. The students should specify the mathematical model of the problem, use MATLAB’s symbolic manipulation capabilities to derive the partial derivatives of the functions, and solve the problem iteratively using the Newton-Raphson method. All the steps of the solution are implemented in MATLAB programs. The second question involves the calculation of the dew point temperature for the same nonideal binary system that was used in question 1. The method of solution is similar to the solution of question 1, except that in this case there are three simultaneous nonlinear algebraic equations and the partial derivatives (for the Jacobian matrix) are calculated using finite differences.

After finishing the exam the students turn in the exam form, where their individual data are specified, and all the MATLAB files that were used for the solution. The MATLAB programs provide clear and precise documentation of all the solution steps. Thus, the programs are the best means to assess the knowledge level of the student and to grade the exam.

Problems, such as this exam problem, were assigned to students in the past as homework assignments for solution with programming languages such as FORTRAN or PASCAL. Typically two or three weeks were allocated to complete the assignment. The same problems can be solved today in two hours in the tense atmosphere of an exam. This demonstrates the advantages of the new software tools and programming languages and the new approaches presented here for numerical problem solving.

### 6. A FRAMEWORK FOR INCORPORATING COMPUTATION TOOLS OF VARIOUS SCALES IN THE UNDERGRADUATE CURRICULUM

A proposed framework for integrating computation tools of various scales into the curriculum is shown in Table 1. The

<table>
<thead>
<tr>
<th>No.</th>
<th>Course Name</th>
<th>Recommended software and/or database</th>
<th>Purpose</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction to Modeling and Computation</td>
<td>POLYMATH</td>
<td>Solution of SMSA problems, Regression and statistical analysis</td>
<td>Shacham,[20] Cutlip and Shacham[21]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Excel</td>
<td>Parametric studies, Tabular and graphical presentation of results</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MATLAB</td>
<td>Study of programming, Parametric studies, Tabular and graphical presentation of results</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Material and Energy Balances</td>
<td>Process Simulator</td>
<td>Simple design project</td>
<td>Dahm, et al.[15]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DIPPR and NIST</td>
<td>Reliable physical property data, Units and experimental errors</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Thermodynamics</td>
<td>Process Simulator</td>
<td>Selecting the right thermodynamic package for the system, Multiphase equilibrium</td>
<td>Dahm, et al.[15]</td>
</tr>
<tr>
<td>4</td>
<td>Equilibrium Stage operations</td>
<td>Instructor-prepared MATLAB and Mathematica programs</td>
<td>Visualization of graphical solution techniques for pedagogical purposes</td>
<td>Joo and Choundary[13], Rasteiro, et al.[14]</td>
</tr>
<tr>
<td>5</td>
<td>Fluid Dynamics &amp; Heat transfer</td>
<td>CFD software</td>
<td>Numerical experimentation, Visualization of the flow phenomena</td>
<td>Edgar[1]</td>
</tr>
<tr>
<td>6</td>
<td>Unit Operations Laboratory</td>
<td>Pre-prepared simulation programs</td>
<td>Virtual laboratory experiments complementing “hands on” experiments</td>
<td>Wiesner and Lan[18]</td>
</tr>
<tr>
<td>7</td>
<td>Process control, and process control</td>
<td>MATLAB toolbox &amp; SIMULINK, Dynamic simulation programs</td>
<td>Control theory related exercises, Virtual laboratory experiments complementing “hands on” experiments.</td>
<td>Edgar[1]</td>
</tr>
<tr>
<td></td>
<td>laboratory</td>
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<tr>
<td>8</td>
<td>Molecular Modelling</td>
<td>Molecular simulation programs</td>
<td>Virtual experiments</td>
<td>Edgar[1]</td>
</tr>
<tr>
<td>9</td>
<td>Process and Product Design</td>
<td>Commercial simulation, design, and optimization programs</td>
<td>Interactive process and product design and optimization, Validation of the design through the simulation program</td>
<td>Seider, et al.[18], Rockstraw[20]</td>
</tr>
</tbody>
</table>
main feature of the new framework is a basic computational course that replaces the traditional computer programming course. This course has been described in section 4.

Further enhancement of the knowledge acquired in the introductory course can be achieved by using the packages in other modeling and computation-oriented courses. These include courses in numerical methods, optimization, process simulation, dynamics and control, and advanced math. The software packages POLYMATH, Excel, and MATLAB can be used throughout the curriculum for solving problems of various complexities (SMSA, MMSA, etc) and for correlation of data via multiple linear, polynomial, and nonlinear regressions. A detailed demonstration is available of the use of various software packages for multi-scale modeling in a problem involving a biokinetic modeling of imperfect mixing in a Chemostat and the optimization of its operation.\[31\]

In the first chemical engineering course (Material and Energy Balances), it is desirable to introduce physical property databases (such as NIST and DIPPR) to encourage the use of reliable data sources, considerations of the units associated with the various properties, and awareness of the experimental errors associated with their values. Process simulation programs (such as HYSYS or Aspen) can be used for mini-projects as recommended by Dahm, \textit{et al.}\[15\]

Additional software packages (such as commercial dynamic and steady-state process simulation, optimization, design, CFD, and molecular simulation), as well as instructor-prepared demonstration programs, can be introduced into the various courses of the ChE curriculum as shown in Table 1. In these courses, the objectives are to use the programs for numerical, model-based, and virtual experimentation, analysis of cause-effect relationships in complex systems, and visualization of challenging concepts. The packages can be introduced to the students in a time-efficient and effective way while simultaneously enabling a better understanding of the specific course material.

6. CONCLUSIONS

A review of the state of the art of chemical engineering computing in academia and in industry has demonstrated that incorporating efficient and widely used computing tools into the undergraduate curriculum remains a continuing major challenge to educators. We suggest that a combination of three popular packages can be integrated into a basic computational course that enables the solution of problems of increasing complexity in the educational setting. These same software packages are also widely used by chemical engineering professionals.

The suggested approach is valid for simple SMSA problems to rather complicated MMMA problems. Shacham\[20\] has shown that the same three software packages can be used for instruction in programming including modeling and parametric studies as well as regression and statistical data analysis. The described combination of these packages also fulfills most of the basic computational needs in the undergraduate chemical engineering curriculum and in engineering practice.

The presented framework also enables and encourages the inclusion of additional software tools and databases within the undergraduate curriculum as part of the regular courses. The proposed framework represents a proper balance between the educational computing necessary for the chemical engineering curriculum and the requisite professional computing capabilities expected of current graduates.

REFERENCES


37. Shacham, M., “Applying New Technologies to the Classroom—What Have We Learned from Past Experience?”, Paper 133a, Presented at the AIChE100 Annual Meeting, Philadelphia, PA, Nov. 16-21, 2008 (also available at <http://cee.che.ufl.edu/>)

DEVELOPMENT OF CONTEMPORARY PROBLEM-BASED LEARNING PROJECTS

In Particle Technology

ANDREW T. HARRIS
University of Sydney • NSW, 2006, Australia

Recently, there have been attempts by several prominent engineers to raise awareness of the need for curriculum renewal in chemical engineering [1, 2]. In this context, the University of Sydney redesigned its undergraduate curriculum in 2004 to be more relevant to the educational needs of tomorrow’s engineers [3]. This process involved an examination of what was taught, how it was delivered, and how students learned this material. As a result, a significant proportion of the revised curriculum was based upon the principles of Problem-Based Learning (PBL), i.e., learning driven by the solution of open-ended problems. The new curriculum was rolled out from the beginning of 2005 and has been well received by students, academics, and industry alike.

In chemical engineering, the application of PBL is neither novel nor particularly controversial [4, 5]. To our knowledge, however, there are no published examples of the application of PBL in particle science and technology. We estimate that >75% of all industrial processes involve the processing of particles of some description, e.g., powders, solid particles in fluids, polymers (emulsions), and biological systems (cells), and therefore consider this a worrying deficiency.

The core concepts and applications of particle science and technology were historically taught in the second semester of the penultimate (i.e., third) year at Sydney using a traditional teaching and learning approach, i.e., lectures and associated short tutorials, with small assignments throughout the semester and a final, graded examination. This course made use of several excellent textbooks [6-8]; however there was little integration, either with other subjects in the same semester, or material taught in other years. While the timing has remained the same, the new structure developed at Sydney now has strong integration within and across the four years of the curriculum.

Particle science and technology is now taught in the same semester as chemical product design, process design, process economics, project management, risk assessment, decision making, and entrepreneurship. This material is delivered in three administratively separate, but practically linked courses, which cover the basic fundamentals, enabling technologies, and engineering practice [9] in accordance with the design of Sydney’s new curriculum. These courses are compulsory for all undergraduate chemical engineers and have a value of 6 credit points; the standard across the University of Sydney. The typical enrolment is around 50 students and the course was run for the first time in 2005. The structure and content for second-semester, third-year is summarized in Table 1.

Andrew Harris is an associate professor at the University of Sydney and director of the Laboratory for Sustainable Technology, a multidisciplinary research group with interests in sustainable process development and nanomaterials. At Sydney, he lectures in product design, particle technology, and “green” engineering and makes extensive use of problem-based learning in all of these areas.

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Chemical Engineering Education
This paper concerns the chemical engineering practice course (CHNG3807 in Table 1), in which the goal is to integrate the concepts and enabling techniques learned in the other courses through a series of projects. In this paper we discuss some of the background leading to the development of this course, describe the teaching, learning, and assessment rationale, and then briefly present the two major projects offered to students in 2005 and 2006. Finally, we conclude with an assessment of student reaction to the course, in terms of content and delivery.

TEACHING AND LEARNING METHODOLOGY

Harris and Briscoe-Andrews[4] have previously reported on the development of an advanced (postgraduate) course in chemical engineering delivered using the PBL methodology. The application of PBL in the chemical engineering undergraduate syllabus has also received attention.[4,5] PBL is a generic, student-centered, contextualized approach to learning,[10] whose forms may include research, case studies, guided design, engineering design projects, and small self-directed learning groups.[4,5] Woods has reported that in PBL the majority of time is spent learning—by identifying what you need to know, finding out, teaching each other, and then applying your new knowledge.[4] Thus, the primary aim of the exercise is the learning, not the completion of the project. The project is simply the means to this end.[4] In our work, the PBL methodology was developed in conjunction with medical education specialists at the University of Nottingham in the United Kingdom.[11] PBL has previously been reported to enhance teaching and learning outcomes in medicine.[10] This approach emphasizes: i) independent student learning (both individually and in small groups); ii) rigorous project formulation, problem definition, and project work plans; iii) discursive sessions; and iv) regular submissions with timely feedback.

In CHNG3807 our aim was to introduce students to the types of problems the modern chemical engineer is asked to solve, and to use these to drive student learning in product design, particle science, and technology. The subject matter is contemporary and the projects integrate key concepts across the curriculum, in particular linking with CHNG3805 and CHNG3806 (Table 1), while drawing heavily on material learned in earlier years (particularly mass and energy balances, thermodynamics, physical chemistry, physics and mechanics, mathematics and numerical methods, and an ability to write coherent reports based on qualitative and quantitative information).

Typically three projects are used; the first on product design (usually a four-week study on the development of water treatment technologies for remote communities), the second a short (one-week) project on innovation and entrepreneurship and then finally a major (eight-week) project focusing on particle science and technology. Over the past four years we have developed two major projects that are offered in alternating years: i) the design of a zero-emission coal power

<table>
<thead>
<tr>
<th>Course code and title</th>
<th>Syllabus</th>
<th>Summary of teaching and learning approach</th>
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| CHNG3805, Chemical Product Design | Chemical product design  
Innovation and entrepreneurship  
Particle science (properties and characterization of particles, sampling and measuring particles, single particles falling in fluids, hindered settling, measuring and analyzing particle size distributions, drag coefficients and terminal velocity, particles in fluids calculations)  
Particle technology (cyclone design, particulate transport, pneumatic conveying, packed beds, fluidized beds, storage and flow of powders, hopper design, size change, i.e. reduction and enlargement, filtration, surface activity). | Lectures and tutorials, assignments and a midsemester examination. Course is competency based (i.e., pass/fail) with a final barrier examination at the end of semester. |
| CHNG3806, Management of Industrial Systems | Process engineering economics (Economies of scale, Cost estimation methods, Economic forecasting, Economic evaluation of projects, plans and processes, Business risk and uncertainty, Depreciation and tax provision)  
Risk assessment (Loss and waste prevention, Occupational health and safety, Concepts of hazard analysis).  
Project management (PM approaches and tools, Multi-objective optimization and trade-off analysis, Supply chain and value chain management, Life cycle management). | Lectures and tutorials, assignments and a midsemester examination. Course is competency based (i.e., pass/fail) with a final barrier examination at the end of semester. |
| CHNG3807, Chemical Engineering Practice II (Products and Value Chains) | Incorporates aspects of all of the material from CHNG3805 and CHNG3806 (above) with material from the first and second years of the curriculum into open ended projects. | Graded, project based assessment, involving a mixture of individual and group work. No final examination. |
station, and ii) the design of a large-scale carbon nanotube synthesis facility. These offerings were designed to address "issues of scale" in chemical engineering, from molecular to macro-systems levels.

Both major projects draw heavily on our research interests and expertise. This is advantageous for several reasons—e.g., we can present cutting-edge material to students to keep them interested throughout their studies—but mainly because we have available to us a bank of skilled and knowledgeable tutors, who are intimately familiar with the material being studied through their own Ph.D. research. We have previously reported that this is also advantageous for monitoring instances where students, either advertently or inadvertently, are guilty of plagiarism. Because the course material (and underlying published reference material) is very well known to the teaching and learning staff, it is comparatively simple to identify cases where plagiarism has occurred.[9]

**ASSESSMENT**

In our experience, most students only learn when they have to. The structure of the revised curriculum at Sydney (where there are major projects every semester) helps students to put into practice the concepts they have learned and is, in our opinion, an effective extension of learning from theory and tutorials. Not only does it provide students with an opportunity to understand how these concepts are used but also broadly identifies for them how this knowledge relates to other parts of their degree, well before they undertake their capstone design course.

For each case, students were presented with a technologically complex, real-life situation with no single correct answer. Their challenge was to develop a solution that was technologically complex, real-life situation with no single correct answer. The numerical scores from these assessments were then factored into the final project mark awarded to each student by adjusting their mark either up or down, according to their deviation from the mean group mark determined from the peer and self assessments. Historically, the maximum deviation in marks across a group has been 20%.

**MAJOR PROJECTS IN PARTICLE TECHNOLOGY**

To give an idea of the working process for each project, we present the two major case studies used in 2005 and 2006, on zero-emission coal electricity and the large-scale production of carbon nanotubes, respectively. Both cases were the major assessment item in their respective years, valued at 70% of the course mark.

Each project began with a (very broad) statement of the problem and was typically supported by a keynote lecture, learning topics, lists of keywords and references, lecture and workshop materials, experimental data, and Web sites of interest—although this material was not all made available initially; students had to specifically request it. The cases were real-world problems, i.e., they were complex and open-ended, with incomplete data, and required rapid generation and rejection of solution alternatives. They were also framed within a real-world context, i.e., they incorporated aspects of safety, economics, ethics, regulation, intellectual property, and market and social needs. Furthermore, both technical and nontechnical attributes were emphasized during the projects. This required students to develop and demonstrate technical knowledge as well as generic skills in research and enquiry, information literacy, personal and intellectual autonomy, communication, and ethical, social, and professional understanding, consistent with the teaching and learning aims of the University of Sydney.

**Zero-Emission Coal**

This project began with an introductory lecture on energy supply and demand and the available technologies to meet this demand into the future. Australia has a cheap, plentiful supply of coal sufficient to last hundreds of years, even considering future demand. Thus, the coal industry plays a major role in Australia, both economically and as an employer of engineers. Coal is an unsustainable resource, however, which when burned contributes to the problem of global warming through enhanced emissions of CO$_2$. One of the options being examined, in Australia and elsewhere, is to develop "zero-emission" coal processes. In essence this involves the capture and sequestration of the CO$_2$ emissions. Following
this lecture and background information students were given the following brief:

"You are a design engineer working as part of the lead design team for a firm of consulting engineers. Your client, a large Australian mining and energy company, has commissioned your firm to design a 'next generation' coal-fired power plant. Your task is to prepare a preliminary design report for this process. The report should outline the new technology, compare it with other suitable approaches, and give supporting design calculations, where appropriate."

For this project students were allowed to choose their own groups. We have used other strategies to form groups, including random assignment and seeding according to ability (so each group has a range of abilities). We have found no appreciable differences in performance across groups using any of these techniques, however — i.e., individual students tend to achieve a mark consistent with their historical performance irrespective of the other group members — and so we have tended to use the simplest approach to forming groups. Once students had received the brief and formed into groups, the class ended for the day. In most years the teaching and learning staff are asked for the design basis (i.e., how big is the plant) before this happens, but not always.

The next class, held two days later, was a three-hour workshop (as were all the remaining student-staff contact sessions for the project — there are two of these sessions timetabled each week) where students could begin to formulate the exact problem they had to solve. This process typically takes one week and involves extensive examination of the issues, suggestions and rejection of ideas, and discussion with the teaching and learning staff. Following this process, which occurs with individual groups, not the class as a whole, we agreed on a set of objectives for the project, as follows:

Prepare a preliminary design report for a zero-emission coal technology giving supporting design calculations for the i) fluidized bed gasifier, ii) feed storage and iii) handling system, iv) calcination reactor, v) gas clean-up, and vi) carbon sequestration reactor. Another company will design the fuel cell. The design basis is 500,000 tpa (dry basis, coal feed). A block diagram of the system is given in Figure 1. The preliminary design report should include: i) a description of the basic technology, how it works, the underpinning chemistry, and a literature review of possible alternate designs; ii) a process flow diagram (PFD) incorporating mass and energy balances.

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**Figure 1.** Sketch of the zero-emission coal reactor and ancillaries.
(but not a process and instrumentation diagram, P&ID); iii) order of magnitude (± 25%) sizing and performance calculations for each of the unit operations in Figure 1, i.e., coal and calcium oxide storage and feed systems, hopper, rotary valve and pneumatic conveying system, pneumatic conveying system between the gasifier and the calcination reactor, fluidized bed gasification reactor, gas cleaning cyclones and electrostatic precipitator, carbon sequestration reactor (a high pressure slurry reactor); and iv) preliminary (±25%) capital and operating cost estimates for the plant.

Students were then also given the usual guidelines about the length of the report, its structure, appropriate referencing, and warnings about the consequences of plagiarism.

The design reports and accompanying presentations were generally of a high standard, reflecting the effort put into them.

Large-scale Carbon Nanotube Synthesis

Carbon nanotubes are a form of crystalline carbon with unique properties, which make them potentially valuable in a wide range of end-use applications. Currently, research into nanotubes and their applications is hampered by the lack of a suitable technique for manufacturing them in large quantities, which we have defined previously as being of the order of 10 000 tons per plant per year.[12] There are three established methods for CNT synthesis: (i) arc discharge, (ii) laser ablation, and (iii) chemical vapor deposition (CVD). Of these, CVD techniques show the greatest promise for economically viable, large-scale synthesis, based on yields reported in the literature and the inherent scalability of similar technologies, e.g., fluidized catalytic cracking. In particular, the fluidized-bed CVD technique (where the CVD reaction occurs within a fluidized bed of catalyst particles) has the potential to produce high-quality CNTs, inexpensively, in large quantities.[12]

The structure and working process for this project was identical to that for the zero-emission coal study described above. To begin, students were given an introductory lecture on nanotechnology and carbon nanotubes, and then were issued with the following brief:

“You are a design engineer working for a start-up ‘nanotech’ company. Your company has acquired the IP (patents and other information) for a laboratory-scale (1 kg/day) fluidized-bed carbon nanotube synthesis process. Your first job for the company is to assist with the preliminary design for a commercial-scale (5000 kg/day) nanotube synthesis process using this technology. A sketch of our technology is attached (Figure 2).”

![Diagram of carbon nanotube synthesis facility](Figure 2. Sketch of the carbon nanotube synthesis facility.)
After the usual process of rapid idea generation, rejection, and adaptation, the teaching and learning staff and students arrived at a mutually agreed project brief, as follows:

Prepare a preliminary design report for a carbon nanotube manufacturing facility that: i) outlines the technology, how it works, the underpinning chemistry, and possible alternate designs; ii) assesses its performance (including the production of a PFD with mass and energy balances), and gives supporting information (order of magnitude, ± 25% sizing and performance calculations) for the fluidized bed CVD reactor, catalyst preparation system (slurry reactor, drier, and furnace), catalyst storage, handling and feed system (hoppers, rotary valve, and pneumatic conveying system), product purification system (slurry reactor and nano-filtration) and gas clean-up system (cyclones, electrostatic precipitator, and wet scrubber). Capital and operating costs (±25%) were also required.

Again, the design reports and presentations were of a comparatively high standard.

STUDENT FEEDBACK

Student feedback via the formal course evaluation (a confidential paper-based survey containing 12 questions, managed by the University’s Teaching and Learning center) showed that in 2005 (the first time the course was run), overall student satisfaction with the course was below average, with only 21% of students agreeing or strongly agreeing with the statement “Overall I was satisfied with the quality of this unit of study,” although this increased to 43% in 2006 (no data are available for 2007). This compares with 39% who disagreed or strongly disagreed with this statement (31% in 2006). These scores are partly attributable to several factors: i) a perceived high workload relative to their other classes (69% agreed or strongly agreed with the statement “The workload in this unit of study was too high” in 2005; 71% in 2006); ii) the fact this was the first time students had been substantially exposed to the PBL methodology in their studies (many students made individual comments that they would have preferred more lectures and tutorials and fewer project workshops); and iii) a perception that their prior learning had not adequately prepared them for this type of course (41% agreed or strongly agreed with this statement in 2005; 50% in 2006).

Students did report, however, that they were very satisfied with the way the course helped them develop valuable generic attributes, e.g., research inquiry skills, communication skills, and intellectual autonomy (76% agreed or strongly agreed with the statement “This unit of study helped me develop valuable generic attributes” in 2005; 83% in 2006). They also indicated they could see the relevance of the course to their broader education (66% in 2005; 91% in 2006). We take this as an indication that students knew the course was good for them, they just didn’t like it very much because it was difficult. We have continued to streamline and improve the course, in particular including an experimental component where students can gather yield and kinetic data for the production of carbon nanotubes, which they then use in their design calculations.

Our goal for students at the end of the course was that they should be proficient at:

i) developing a strategy for taking a product development idea from concept to commercial artifact, with a comprehensive appreciation of economic arguments, underlying uncertainties (and mitigation of these), and consideration of trade-offs inherent in this development – and demonstrating this in project mode;

ii) applying design and analysis tools for the synthesis of particulate products leading to manufacture of a preferred product at pilot scale – and demonstrating this in project mode;

iii) developing a strategy for design and analysis of extended business enterprises, with a focus on value chain optimization - and demonstrating this in project mode;

And should have developed:

iv) improved research skills and an ability to cope with ambiguity;

v) an ability to select appropriate engineering principles to solve open-ended problems;

vi) engineering practice skills.

We do not have an opportunity to include an assessment of these in the formal course evaluation, but operate our own (non-confidential) questionnaire with students at the completion of the course to help assess this. This survey contains most of the same questions as the formal evaluation (we use this as a sort of internal benchmark) and uses the same response format, but also includes questions on the specific teaching and learning objectives (iv, v and vi above). During this survey, a majority of students in both 2005 and 2006 indicated that they had improved their abilities in these areas. In 2005, 71% of students agreed or strongly agreed with the statement “The problem-based learning style helped me develop important skills and cope with ambiguity.” In 2006 the number was 75%. In both years no student disagreed with this statement.

CONCLUSIONS

Knowledge of the processing behavior of particles is important for most practicing chemical engineers. To this end, the University of Sydney has developed an undergraduate course in particle science and technology using a problem-based learning methodology. Students found the course challenging, but rated highly the generic attributes the teaching and learning style helped them develop.

ACKNOWLEDGMENTS

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REFERENCES

Faculty and Research

R. Michael Banish; Ph.D., University of Utah
Associate Professor
Crystal growth mass and thermal diffusivity measurements.

Ramon L. Cerro; Ph.D., UC Davis
Professor and Chair
Theoretical and experimental fluid mechanics and physicochemical hydrodynamics.

Chien P. Chen; Ph.D., Michigan State
Professor
Lab-on-chip microfluidics, multiphase transport, spray combustion, computational fluid dynamics, and turbulence modeling of chemically reacting flows.

Krishnan K. Chittur; Ph.D., Rice
Professor
Biomaterials, bioprocess monitoring, gene expression bioinformatics, and FTIR/ATR.

James E. Smith Jr; Ph.D., South Carolina
Professor
Ceramic and metallic composites, catalysis and reaction engineering, fiber optic chemical sensing, combustion diagnostic of hypergolic fuels, and hydrogen storage.

Katherine Taconi; Ph.D., Mississippi State
Assistant Professor
Biological production of alternative energy from renewable resources.

Jeffrey J. Weimer; Ph.D., MIT
Associate Professor
Adhesions, biomaterials surface properties, thin film growth, and surface spectroscopies.

David B. Williams; Sc.D., Cambridge
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Kaushal Rege, Ph.D., Rensselaer Polytechnic Institute.
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Daniel E. Rivera, Ph.D., Caltech.
Control systems engineering, dynamic modeling via system identification, robust control, computer-aided control system design, supply chain management
Michael R. Sierks, Ph.D., Iowa State.
Protein engineering, biomedical engineering, enzyme kinetics, antibody engineering
Bryan Vogt, Ph.D., Massachusetts
Nanostructured materials, organic electronics, supercritical fluids for materials processing, moisture barrier technologies

Affiliate/Research Faculty
Paul Johnson, Ph.D., Princeton.
Chemical migration and fate in the environment as applied to environmental risk assessment and the development, monitoring and optimization of technologies for aquifer restoration and water resources management
Bruce E. Rittmann, Ph.D., N.A.E., P.E., Stanford.
Environmental biotechnology, microbial ecology, environmental chemistry, environmental engineering
Jonathan D. Posner, Ph.D., University of California-Irvine
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For Additional Information, Contact:
Dr. J. Azaiez, Associate Head, Graduate Studies
Department of Chemical and Petroleum Engineering
University of Calgary, Calgary, AB, Canada T2N 1N4
gradstud@ucalgary.ca; www.schulich.ucalgary.ca/ench/

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Faculty Research Areas

Akua Asa-Awuku (Georgia Tech): cloud formation, secondary organic aerosols, global climate change

Wilfred Chen (Caltech): biomolecular engineering, biomaterials, nanobiotechnology, drug discovery

David Cocker (Caltech): atmospheric aerosol formation, gas-to-particle conversion, emissions

David Cwiertny (Johns Hopkins): water quality engineering, interfacial processes and pollutant transformation

Robert Haddon (Penn State): electronic structure and properties of molecules and materials, new materials, nanodevices

David Kisailus (UC Santa Barbara): synthesis of novel materials using biomimetic and biospired approaches, nanotechnology

Mark Matsumoto (UC Davis): water and wastewater treatment, hazardous waste site remediation

Ashok Mulchandani (McGill): nanobiotechnology, biosensors, environmental biotechnology

Nosang Myung (UCLA): synthesis of nanoengineering materials, thermoelectrics, spintronics, NEMS/MEMS, gas and biosensors

Joseph Norbeck (Nebraska): synthetic sustainable transportation fuels, air quality impact of vehicle emissions

Sharon Walker (Yale): microbial and nanoparticle adhesion and transport phenomena in aquatic environments

Jianzhong Wu (UC Berkeley): molecular modeling and design, theory of complex fluids, DNA/RNA packaging

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Graduate Coordinator
Department of Chemical Engineering
Case Western Reserve University
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Cleveland, OH 44106-7217
chemeng@case.edu
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INSTITUTES

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- Polymeric materials (Dorgan, Wu, Liberatore)
- Colloids and complex fluids (Marr, Wu, Liberatore)
- Electronic materials (Wolden, Agarwal)
- Molecular simulation and modeling (Ely, Wu, Sum)

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- Microfluidics (Marr, Neeves)
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- A.M. Dean (Harvard 1971)
- J.R. Dorgan (Berkeley 1991)
- J.F. Ely (Indiana 1971)
- A. Herring (Leeds 1989)
- C.A. Koh (Brunel 1990)
- D.W.M. Marr (Stanford 1993)
- R.L. Miller (CSM 1982)
- K.R. Neeves (Cornell 2006)
- E.D. Sloan (Clemson 1974)
- A.K. Sum (Delaware 2001)
- J.D. Way (Colorado 1986)
- C.A. Wolden (MIT 1995)
- D.T. Wu (Berkeley 1991)
Research Areas
Bioanalytical Chemistry
Biofuels and Biorefining
Biomaterials
Cell and Tissue Engineering
Magnetic Resonance Imaging
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Synthetic and Systems Biology

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.
James C. Linden, Ph.D., Iowa State U.
Christie Peebles, Ph.D., Rice U.
Ashok Prasad, Ph.D., Brandeis U.
Kenneth F. Reardon, Ph.D., Caltech
Brad Reisfeld, Ph.D., Northwestern U.
Qiang (David) Wang, Ph.D., U. Wisconsin
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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.

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Located in Fort Collins, Colorado State University 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
DELAWARE Graduate Studies in Chemical Engineering

Chemical Engineering at Delaware is ranked, by all metrics, in the top 10 programs in the US with world-wide reputation and reach. Built on a long and distinguished history, we are a vigorous and active leader in chemical engineering research and teaching. Our graduate students work with a talented and diverse faculty, and there is a correspondingly rich range of research and educational opportunities that are distinctive to Delaware. We currently have 24 full time faculty, over 100 graduate students, nearly $12M in annual research expenditures, and publish well over 100 scientific manuscripts and patents per year. The range of research varies tremendously—from biomolecular and metabolic engineering to catalysis, energy, green engineering, nanostructured materials, complex fluids engineering and polymers—advances are being made in each area at Delaware. Finally, Delaware is one of the top chemical engineering departments in the US in terms of faculty diversity, and is among the largest producers of Chemical Engineering PhD students in the US.

UNIVERSITY of DELAWARE

GRADUATE EDUCATION at Delaware offers unique opportunities for professional development, including

» The Teaching Fellows program
» Participation in national and international conferences and workshops
» Two annual student-run Departmental symposia

The Teaching Fellows program promotes the development of the next generation of academic educators and scholars by enabling graduate students to co-teach Chemical Engineering courses with a faculty mentor.

The graduate symposia are run by our graduate student organization, the Colburn Club, which also organizes social activities and recruiting events within the Department.

All graduate students are supported as research assistants, and are provided a comfortable stipend for living expenses. Special competitive fellowships are available to the best qualified applicants.

INDUSTRIAL COLLABORATIONS are a hallmark of our Department. Many research groups collaborate with local and national industrial laboratories.

This blend of academic and applied engineering research gives our students a unique perspective that is useful in academic or industrial careers. We are close to major chemical and pharmaceutical industry leaders.

CENTERS AND PROGRAMS provide unique environments and experiences for graduate students. These include:

» Delaware Biotechnology Institute (DBI)
» Center for Catalytic Science and Technology (CCST)
» Center for Molecular and Engineering Thermodynamics (CMET)
» Center for Neutron Science (CNS)
» Center for Composite Materials (CCM)
» Chemistry-Biology Interface (CBI)
» Institute for Multi-Scale Modeling of Biological Interactions (IMMBI)
» Solar Hydrogen IGERT

INTERDISCIPLINARY work is done at the interfaces between major research fields, often through close collaborations among the faculty and other departments.

AFTER GRADUATION our graduates find fulfilling careers in academia and industrial research, as well as in law, medicine, and business.

Academia—Our graduates hold positions at top-ten research institutions, as well as in many other programs world-wide.

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DEPARTMENT RECOGNITION

» #9 (2009 U.S. News & World Report)
» #3 (National Research Council, 1994)
» 14 NSF CAREER and Presidential Young Investigator Award Winners
» 3 National Academy of Engineering (NAE) Members
» 11 Named Professors

LOCATION The University of Delaware has a college-town atmosphere, yet we are centrally located between New York City and Washington, D.C., at the heart of the east coast’s chemical and pharmaceutical industries.

APPLICATION to the graduate program is coordinated through the University's Office of Graduate Studies. The application can be found at www.udel.edu/gradoffice/applicants. Admissions are rolling, and the application deadline is March 15 (earlier applications are strongly encouraged.)

Browse our site www.che.udel.edu for updated news and information on our graduate program, faculty research and alumni achievements!

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» Catalysis and Energy
» Metabolic Engineering
» Systems Biology
» Soft Materials, Colloids and Polymers
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» Process Systems Engineering
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The Technical University of Denmark (DTU) is a modern, internationally oriented technological university placed centrally in Scandinavia’s Medicon Valley – one of the world’s leading biotech clusters. It was founded in 1829 by H. C. Ørsted. The University has 6000 students preparing for their BSc or MSc degrees, 600 PhD students and takes 400 foreign students a year on English-taught courses. The DTU campus is located close to the city of Copenhagen, the capital of Denmark.

Chemical Engineering focus areas of research and the research groups are:

- Applied Thermodynamics
- Aerosol Technology
- Bio Process Engineering
- Catalysis
- Combustion Processes
- Emission Control
- Enzyme technology
- Membrane Technology
- Polymer Chemistry & Technology
- Process Control
- Product Engineering
- Oil and Gas Production
- Systems Engineering
- Transport Phenomena

The Department of Chemical Engineering (KT) is a leading research institution. The research results find application in biochemical processes, computer-aided product and process engineering, energy, enhanced oil recovery, environment protection and pollution abatement, information technology, and products, formulations & materials.

The department has excellent experimental facilities serviced by a well-equipped workshop and well-trained technicians. The Hempel Student Innovation Laboratory is open for students’ independent experimental work. The Unit Operations Laboratory and pilot plants for distillation, reaction, evaporation, crystallization, etc. are used for both education and research. Visit us at http://www.kt.dtu.dk/English.aspx.

Graduate programs at Department of Chemical and Biochemical Engineering:

- Chemical and Biochemical Engineering
  - http://www.kt.dtu.dk/cbe
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Stig Wedel sw@kt.dtu.dk
Erling H. Stenby ehs@kt.dtu.dk
Georgios Kontogeorgis gk@kt.dtu.dk
Faculty

Cameron F. Abrams
PhD, University of California-Berkeley
molecular biology, molecular simulations, polymer diffusion, cellular biophysics

Kenneth K.S. Lau
PhD, University of Massachusetts Institute of Technology
physics, nanotechnology, polymer thin films and coatings, chemical vapor deposition

Jason B. Baxter
PhD, University of California Santa Barbara
transport in polymers, biodegradable polymers, transport modeling, coatings, renewable energy

Richard A. Cairncross
PhD, University of Minnesota
transport in polymers, biodegradable polymers, transport modeling, coatings, renewable energy

Anthony M. Lowman
PhD, Purdue University
biomaterials, drug delivery, hydrogels

Nily R. Dan
PhD, University of Minnesota
genome and drug delivery, polymer nano-composites, complex fluids

Raj Mutharasan
PhD, Drexel University
biochemical engineering, cellular metabolism, energy, biocomposites

Giuseppe I. Palmese, Head
PhD, University of Delaware
living polymer systems, nanostructured polymers, materials from renewable sources, composites and interfaces

Masoud Soroush
PhD, University of Michigan
process systems engineering, polymer engineering, modeling simulations

Steven P. Wrenn
PhD, University of Delaware
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M.M. Tomadakis, Ph.D.
M.E. Pozo de Fernandez, Ph.D.
J.R. Brenner, Ph.D.
S. Dutta, Ph.D.

**Research Interests**
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Alternative Energy Sources
Materials Science
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Department of Chemical Engineering
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Affiliated Research Centers:

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http://www.nanohealthalliance.org/

Western Regional Center of Excellence for Biodefense and Emerging Infectious Diseases
http://rce.swmed.edu/rce6/theme_1.htm

National Large Scale Wind Turbine Testing Facility
http://www.thewindalliance.com

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For more information: Visit: www.chee.uh.edu
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Chemical and Biomolecular Engineering
Graduate Admission
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The Department of Chemical and Biological Engineering (ChBE) at Illinois Institute of Technology (IIT) offers everything a student could want in a graduate program: internationally respected faculty, cutting-edge research centers, and joint collaborations with major laboratories, global companies, and other leading universities. Located just minutes from downtown Chicago, IIT gives ChBE students the best of both worlds, with a thriving city known for its culture and social activities, and a prominent research university dedicated to solving the most complex challenges facing society.

ChBE offers graduate certificate, master of science, professional master, and Ph.D. programs in chemical engineering, biological engineering, energy, pharmaceutical engineering and food process engineering. Within each degree program, students have the ability to concentrate their studies and research into a variety of disciplines, ranging from polymer engineering, fuel cell technology, and drug delivery to biosensors, renewable energy, and particle processing.

The department is actively and continuously committed to making positive and important contributions to society by providing the best possible education to all its students, and by offering the highest quality of scholarship through research activities at the forefront of scientific and technological knowledge. ChBE is devoted to fostering the next generation of chemical and biological engineers, instilling in them a quest for innovation and a thirst for problem solving.

**Faculty**

Javad Abbasian  
John L. Anderson  
Hamid Arastoopour  
Donald J. Chmielewski  
Ali Cinar  
Dimitri Gidaspow  
Allan S. Myerson  
Satish J. Parulekar  
Victor Perez-Luna  
Jai Prakash, Acting Chair  
Vijay Ramani  
Jay Schieber  
Fouad Teymour  
David C. Venerus  
Darsh T. Wasan

**Research Areas**

Biological Engineering • Energy and Sustainability • Advanced Materials • Systems Engineering • Fuel Cells and Batteries • Fluidization and Gasification • Hybrid Systems • Interfacial and Transport Phenomena • Nanotechnology Systems Engineering • Complex Systems • Advanced Process Control • Process Monitoring

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For more information visit www.chbe.illinois.edu

Or write to:
Department of Chemical and Biomolecular Engineering
University of Illinois at Urbana-Champaign
114 Roger Adams Laboratory, Box C-3
600 South Mathews Avenue
Urbana, IL 61801-3602
Iowa State University’s Department of Chemical and Biological Engineering offers excellent programs for graduate research and education. Our cutting-edge research crosses traditional disciplinary lines and provides exceptional opportunities for graduate students. Our diverse faculty are leaders in their fields and have won national and international recognition for both research and education, our facilities (laboratories, instrumentation, and computing) are state of the art, and our financial resources give graduate students the support they need not just to succeed, but to excel. Our campus houses several interdisciplinary research centers, including the Ames Laboratory (a USDOE laboratory focused on materials research), an NSF Engineering Research Center on chemicals from biorenewables, the Plant Sciences Institute, the Office of Biotechnology, and the Bioeconomy Institute.

The department offers ME, MS, and PhD degrees in chemical engineering. Students with undergraduate degrees in chemical engineering or related fields can be admitted to the program. We offer full financial support with tuition coverage and competitive stipends to all our MS and PhD students. In addition, we offer several competitive fellowships.
Faculty, Ph.D. Institute, Research Areas

- Jennifer L. Anthony, *University of Notre Dame*, advanced materials, nanoporous molecular sieves, environmental separations, ionic liquids, solvent properties
- Vikas Berry, *Virginia Polytechnic Institute and State University*, bionanotechnology, nanoelectronics, sensors
- James H. Edgar (head), *University of Florida*, crystal growth, semiconductor processing and materials characterization
- Larry E. Erickson, *Kansas State University*, environmental engineering, biochemical engineering, biological waste treatment process design and synthesis
- L.T. Fan, *West Virginia University*, process systems engineering including process synthesis and control, chemical reaction engineering, particle technology
- Larry A. Glasgow, *University of Missouri*, transport phenomena, bubbles, droplets and particles in turbulent flows, coagulation and flocculation
- Keith L. Hohn, *University of Minnesota*, catalysis and reaction engineering, natural gas conversion, and nanoparticle catalysts
- Peter Pfommm, *University of Texas*, polymers in membrane separations and surface science
- Mary E. Rezac, *University of Texas*, polymer science, membrane separation processes
- John R. Schlup, *California Institute of Technology*, biobased industrial products, applied spectroscopy, thermal analysis, intelligent processing of materials
- Walter Walawender, *Syracuse University*, activated carbon, biomass energy, fluid particle systems, pyrolysis, reaction modeling and engineering

For additional information:

Graduate Program
Kansas State University
Chemical Engineering
1005 Durland Hall
Manhattan, KS 66506-5102
785-532-5584
che@ksu.edu
www.che.ksu.edu
Research Areas Include:

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- Aerosols
- Biopharmaceutical and Biocellular Engineering
- Energy Resources & Alternative Energy
- Environmental Engineering
- Interfacial Engineering
- Materials Synthesis
- Nanomaterials
- Polymers and Membranes
- Supercritical Fluids Processing

Chemical Engineering Faculty

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R. Andrews · University of Kentucky
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T. Dziubla · Drexel University
E. Gruke · Ohio State University
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S. Rankin · University of Minnesota
A. Ray · Clarkson University
J. Seay · Auburn University
D. Silverstein · Vanderbilt University
J. Smart · University of Texas
T. Tsang · University of Texas

Materials Engineering Faculty

J. Balk · The Johns Hopkins University
M. Beck · Northwestern University
Y.T. Cheng · California Institute of Technology
R. Eitel · The Pennsylvania State University
B. Hinds · Northwestern University
F. Yang · University of Rochester
T. Zhai · University of Oxford

For more information:

Web:  http://www.engr.uky.edu/cme
Address:  Department of Chemical & Materials Engineering
          Director of Graduate Studies
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• signal transduction

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fluid mechanics • heat transfer • applied mathematics

Hugo S. Caram, University 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 University
polymer colloids and films • emulsion copolymerization •
polymer synthesis and characterization

Alice P. Gast, Princeton University
complex fluids • colloids • proteins • interfaces

James F. Gilchrist, Northwestern University
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Vincent G. Grassi II, Lehigh University
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Lori Herz, Rutgers University
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development and manufacturing

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Anand Jagota, Cornell University
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interactions

Andrew Klein, North Carolina State University
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polymerization

Mayuresh V. Kothare, California Institute of Technology
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systems

Ian J. Laurenzi, University of Pennsylvania
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aggregation phenomena

William L. Luyben, University of Delaware
process design and control • distillation

Anthony J. McHugh, University of Delaware
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Jeetain Mittal, University of Texas
protein folding • macromolecular crowding • hydrophobic
effects • nanoscale transport

Susan F. Perry, Pennsylvania State University
cell adhesion and migration • cellular biomechanics

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Cesar A. Silebi, Lehigh University
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Department of Chemical Engineering, Lehigh University • 111 Research Drive, Jacocca Hall • Bethlehem, PA 18015
Fax: (610) 758-5057 • Email: inchegs@lehigh.edu • Web: www.che.lehigh.edu
THE CITY
Baton Rouge is the state capital and home of the state’s flagship institution, LSU. Situated near the Acadian region, Baton Rouge blends the Old South and Cajun cultures. Baton Rouge is one of the nation’s busiest ports and the city’s economy rests heavily on the chemical, oil, plastics, and agricultural industries. The great outdoors provide excellent year-round recreational activities, especially fishing, hunting, and water sports. The proximity of New Orleans provides for superb nightlife, especially during Mardi Gras. The city is also only two hours away from the Mississippi Gulf Coast, and four hours from either Gulf Shores or Houston.

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TO APPLY, CONTACT
GRADUATE COORDINATOR
Cain Department of Chemical Engineering
Louisiana State University
Baton Rouge, Louisiana 70803
Telephone: 1-800-256-2084  FAX: 225-578-1476
e-mail: gradcoor@lsu.edu

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The Department of Chemical and Biochemical Engineering at UMBC offers graduate programs leading to M.S. and Ph.D. degrees in Chemical Engineering. Our research is heavily focused in biochemical, biomed-}
ical, and bioprocess engineering and covers a wide range of areas including fermentation, cell culture, downstream processing, drug delivery, protein engineering, and bio-optics. Unique programs in the regulatory-engineer-
ing interface of bioprocessing are offered as well.

**FACILITIES**
The Department offers state-of-the-art facilities for faculty and graduate student research. These modern facilities have been developed primarily in the last six years and comprise 6,000 square feet of laboratory space in the Technology Research Center plus 7,000 square feet of departmental laboratories in the new Engineering and Computer Science building.

**LOCATION**
UMBC is located in the Baltimore-Washing-
ton corridor and within easy access to both metropolitan areas. A number of government research facilities such as NIH, FDA, USDA, NSA, and a large number of biotechnology companies are located nearby and provide excellent opportunities for research interactions.

**FOR FURTHER INFORMATION**

**CONTACT:**
Graduate Program Coordinator
Department of Chemical and Biochemical Engineering
University of Maryland Baltimore County
1000 Hilltop Circle
Baltimore, Maryland 21250
Phone: (410) 455-3400
FAX: (410) 455-1049

**FACULTY**

**T. BAYLES, Ph.D. Pittsburgh**
Engineering education; k-12 Outreach

**M. CASTELLANOS, Ph.D. Cornell**
Mathematical modeling of biological systems; Biocomplexity; Molecular systems engineering

**D. D. FREY, Ph.D. California-Berkeley**
Biochemical separations; Chromatography of biopolymers

**T. GOOD, Ph.D. University of Wisconsin-Madison**
Cellular Engineering; Protein Aggregation; In Vitro Models of Disease

**J. LEACH, Ph.D. University of Texas at Austin**
Biomaterials; Cell and Tissue Engineering

**M. R. MARTEN, Ph.D. Purdue**
Proteome analysis; Cellular, bioprocess, and biomedical engineering.

**A. R. MOREIRA, Ph.D. Pennsylvania**
rDNA fermentation; Regulatory issues; Scale-up; Downstream processing

**G. F. PAYNE, Ph.D.* Michigan**
Biomolecular engineering; Biopolymers; Renewable resources.

**G. RAO, Ph.D. Drexel**
Fluorescence-based sensors and instrumentation; Fermentation and cell culture.

**J. M. ROSS, Ph.D. Rice**
Cellular and biomedical engineering; Cell adhesion; Tissue engineering

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Graduate Program Director
Department of Chemical Engineering
159 Goessmann Lab., 686 N. Pleasant St.
University of Massachusetts
Amherst, MA 01003-9303

FACULTY:

Surita R. Bhatia (Princeton)
W. Curtis Conner, Jr. (Johns Hopkins)
Paul J. Dauenhauer (Univ. of Minnesota)
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Susan C. Roberts (Cornell)
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Current areas of Ph.D. research in the Department of Chemical Engineering receive support at a level of over $4 million per year through external research grants. Examples of research areas include, but are not limited to, the following.

- **Bioengineering**: cellular engineering; metabolic engineering; targeted bacteriolytic cancer therapy; assembly of biochemical pathways for synthesis of small molecules; systems biology; genetic circuit design...

- **Biofuels and Sustainable Energy**: catalysis, catalytic fast pyrolysis of biomass; catalytic microwave engineering; fuel cells; energy engineering...

- **Fluid Mechanics and Transport Phenomena**: biofluid dynamics and blood flow; hydrodynamics of microencapsulation; mechanics of cells, capsules, and suspensions; modeling microscale flows and transport phenomena; hydrodynamic stability and pattern formation; interfacial flows; gas-particle flows...

- **Materials Science and Engineering**: design and characterization of new catalytic materials; thin film and nanostructured materials for microelectronics and photonics; colloids and biomaterials; rheology and phase behavior of associative polymer solutions; polymeric materials processing...

- **Molecular and Multi-scale Modeling & Simulation**: computational quantum chemistry and kinetics; molecular modeling for nanotechnology; 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 nanostructured materials; systems-level analysis using deterministic and stochastic atomic-scale simulators; modeling and control of biochemical reactors; nonlinear process control theory...

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Graduate Coordinators
Dr. F. Bonner (Chemical Eng.) Francis_Bonner@uml.edu
Dr. G. Brown (Energy Eng.) Gilbert_Brown@uml.edu

Or

UMASS Lowell  Department of Chemical Engineering
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Fax: (514) 398-6678
E-mail: inquire.che2rad@mcgill.ca

D. BERK, Department Chair (Calgary)
Biological and chemical treatment of wastes, crystallization of fine powders, reaction engineering [dimitrios.berk@mcgill.ca]

D. G. COOPER, (Toronto)
Prod. of bacteriophages & biopharmaceuticals, self-cycling ferment., bioconversion of xenobiotics [david.cooper@mcgill.ca]

S. COULOMBE, Canada Research Chair (McGill)
Plasma processing, nano fluids, transport phenomena, optical diagnostic and process control [sylvain.coulombe@mcgill.ca]

J. M. DEALY, Emeritus Professor (Michigan)
Polymer rheology, plastics processing [john.dealy@mcgill.ca]

R. J. HILL, Canada Research Chair (Cornell)
Fuzzy colloids, biomimetic interfaces, hydrogels, and nanocomposite membranes [reghan.hill@mcgill.ca]

E. A. V. JONES, (CalTech)
Biofluid dynamics, biomechanics, tissue engineering, developmental biology & microscopy [liz.jones@mcgill.ca]

M. R. KAMAL, Emeritus Professor (Carnegie-Mellon)
Polymer proc., charac., and recycling [musa.kamal@mcgill.ca]

R. LEASK, William Dawson Scholar (Toronto)
Biomedical engineering, fluid dynamics, cardiovascular mechanics, pathobiology [richard.leask@mcgill.ca]

C. A. LECLERC, (Minnesota)
Biorefineries, hydrogen generation, fuel processing, ethylene prod., catalysis, reaction engineering [corey.leclerc@mcgill.ca]

M. MARIC, (Minnesota)
Block copolymers for nano-porous media, organic electronics, controlled release; “green” plasticisers [milan.maric@mcgill.ca]

J. L. MEUNIER, (INRS-Energie, Varennes)
Plasma science & technology, deposition techniques for surface modifications, nanomaterials [jean-luc.meunier@mcgill.ca]

R. J. MUNZ, (McGill)
Thermal plasma tech, torch and reactor design, nanostructured material synthesis, environmental apps [richard.munz@mcgill.ca]

S. OMANOVIC, (Zagreb)
Biomaterials, protein/material interactions, bio/immunosensors, (bio)electrochemistry [sasha.omanovic@mcgill.ca]

T. M. QUINN, (MIT)
Soft tissue biophysics, mechanobiology, biomedical engineering, adherent cell culture technologies [thomas.quinn@mcgill.ca]

A. D. REY, James McGill Professor (California-Berkeley)
Computational material sci., thermodynamics of soft matter and complex fluids, interfacial sci. and eng. [alejandro.rey@mcgill.ca]

P. SERVIO, Canada Research Chair (British Columbia)
High-pressure phase equilibrium, crystallization, polymer coatings [phillip.servio@mcgill.ca]

N. TUFENKJI, Canada Research Chair (Yale)
Environmental and biomedical eng., bioadhesion and biosensors, bio- and nano-technologies [nathalie.tufenkji@mcgill.ca]

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---

**D. BERK**, Department Chair (Calgary)
Biological and chemical treatment of wastes, crystallization of fine powders, reaction engineering [dimitrios.berk@mcgill.ca]

**D. G. COOPER**, (Toronto)
Prod. of bacteriophages & biopharmaceuticals, self-cycling ferment., bioconversion of xenobiotics [david.cooper@mcgill.ca]

**S. COULOMBE**, Canada Research Chair (McGill)
Plasma processing, nanofluids, transport phenomena, optical diagnostic and process control [sylvain.coulombe@mcgill.ca]

**J. M. DEALY**, Emeritus Professor (Michigan)
Polymer rheology, plastics processing [john.dealy@mcgill.ca]

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Fuzzy colloids, biomimetic interfaces, hydrogels, and nanocomposite membranes [reghan.hill@mcgill.ca]

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Plasma science & technology, deposition techniques for surface modifications, nanomaterials [jean-luc.meunier@mcgill.ca]

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High-pressure phase equilibrium, crystallization, polymer coatings [phillip.servio@mcgill.ca]

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Environmental and biomedical eng., bioadhesion and biosensors, bio- and nano- technologies [nathalie.tufenkji@mcgill.ca]

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Graduate Secretary  
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McMaster University  
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Mississippi State University
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*Source: National Science Foundation/Division of Science Resources Statistics, FY2005, Table 64. **Data compiled March, 2008
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Luis A. N. Amaral, Ph.D., Boston University, 1996
Complex systems, computational physics, biological networks

Linda J. Broadbelt, Ph.D., Delaware, 1994
Reaction engineering, kinetics modeling, polymer resource recovery

Wesley R. Burghardt, Ph.D., Stanford, 1990
Polymer science, rheology

Kimberly A. Gray, Ph.D., Johns Hopkins, 1988
Catalysis, treatment technologies, environmental chemistry

Bartosz A. Grzybowski, Ph.D., Harvard, 2000
Complex chemical systems

Michael C. Jewett, Ph.D., Stanford, 2005
Synthetic biology, systems biology, metabolic engineering

Harold H. Kung, Ph.D., Northwestern, 1974
Kinetics, heterogeneous catalysis

Joshua N. Leonard, Ph.D., Berkeley, 2006
Cellular & biomolecular engineering for medicine, systems biology

William M. Miller, Ph.D., Berkeley, 1987
Cell culture for biotechnology and medicine

Justin M. Notestein, Ph.D., Berkeley, 2006
Materials design for adsorption and catalysis

Monica Olvera de la Cruz, Ph.D., Cambridge, 1984
Statistical mechanics in polymer systems

Julio M. Ottino, Ph.D., Minnesota, 1979
Fluid mechanics, granular materials, chaos, mixing in materials processing

Gregory Ryskin, Ph.D., Caltech, 1983
Fluid mechanics, computational methods, polymeric liquids

Lonnie D. Shea, Ph.D., Michigan, 1997
Tissue engineering, gene therapy

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Adsorption and diffusion in porous media, molecular modeling

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**Xudong Cao**  
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**Marc Dubé**  
*Biodiesel, Polymer Reaction Engineering*

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*Biofluid Mechanics and Reology*

**Kevin Kennedy**  
*Biological Waste Water Treatment*

**Kathlyn Kirkwood**  
*Biofuels, Biochemical Engineering*

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Janna Maranas, Graduate Admissions Chair
158 Fenske Laboratory
Department of Chemical Engineering
The Pennsylvania State University
University Park, PA 16802
814-863-6228 jmaranas@engr.psu.edu

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Ph.D. and M.Eng. Programs in Chemical Engineering

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Ilhan A. Aksay
Jay B. Benziger
Pablo G. Debenedetti
Christodoulos A. Floudas
Yannis G. Kevrekidis
Morton D. Kostin
A. James Link
Yueh-Lin (Lynn) Loo
Celeste M. Nelson
Athanassios Z. Panagiotopoulos
Rodney D. Priestley
Robert K. Prud’homme
Richard A. Register (Chair)
William B. Russel
Stanislav Y. Shvartsman
Sankaran Sundaresan
James Wei

Affiliate Faculty

Emily A. Carter (Mechanical and Aerospace Engineering)
George W. Scherer (Civil and Environmental Engineering)
Howard A. Stone (Mechanical and Aerospace Engineering)

- Applied and Computational Mathematics
  - Computational Chemistry and Materials
  - Systems Modeling and Optimization
- Biotechnology
  - Biomaterials
  - Biopreservation
  - Cell Mechanics
  - Computational Biology
  - Protein and Enzyme Engineering
  - Tissue Engineering
- Environmental and Energy Science and Technology
  - Art and Monument Conservation
  - Fuel Cell Engineering
- Fluid Mechanics and Transport Phenomena
  - Biological Transport
  - Electrohydrodynamics
  - Flow in Porous Media
  - Granular and Multiphase Flow
  - Polymer and Suspension Rheology
- Materials: Synthesis, Processing, Structure, Properties
  - Adhesion and Interfacial Phenomena
  - Ceramics and Glasses
  - Colloidal Dispersions
  - Nanoscience and Nanotechnology
  - Organic and Polymer Electronics
  - Polymers
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  - Chemical Reactor Design, Stability, and Dynamics
  - Heterogeneous Catalysis
  - Process Control and Operations
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  - Complex Fluids
  - Glasses
  - Kinetic and Nucleation Theory
  - Liquid State Theory
  - Molecular Simulation

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Director of Graduate Studies
Chemical Engineering
Princeton University
Princeton, NJ 08544-5263

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- Molecular Modeling & Statistical Mechanics • Nanofabrication & Nanomaterials
- Pharmaceutical Engineering • Polymer Materials & Composites
- Product & Process Systems Engineering • Separation Processes • Surface Science

The School of Chemical Engineering (ChE), the College of Engineering (COE), and Purdue University have been undergoing exciting transformations befitting the dawn of a new century. These changes range from the creation of 95 and 300 entirely new faculty positions in the COE and the university, respectively, and the completion of Discovery Park, a new $350 million multidisciplinary home for research in signature areas of importance to society. In ChE, thirteen new faculty, a mix of freshly minted PhDs, senior academics, and renowned researchers, have joined our ranks since 2003. The current ChE faculty includes five members of the National Academy of Engineering. To house the expanded faculty, students, and research and teaching activities, a new building, the Forney Hall of Chemical Engineering, was completed in 2005 and the original one is undergoing full renovation.

For more information, contact:
Graduate Studies, Forney Hall of Chemical Engineering,
Purdue University
480 Stadium Mall Drive
West Lafayette, IN 47907
Phone: (765) 494-4057
Web: http://engineering.purdue.edu/ChE
Chemical and Biological Engineering at Rensselaer Polytechnic Institute

The Chemical and Biological Engineering Department at Rensselaer 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.E. degree. Programs are also offered in cooperation with the School of Management and Technology which lead to an M.S. in Chemical Engineering and to an MBA or the M.S. in Management. Owing to funding, consulting, and previous faculty experience, the department maintains close ties with industry. Department web site:

http://www.chem.rpi.edu/dept/chem-eng/

Located in Troy, New York, Rensselaer is a private school with an enrollment of some 6000 students. Situated on the Hudson River, just north of New York's capital city of Albany, it is a three-hour drive from New York City, Boston, and Montreal. The Adirondack Mountains of New York, the Green Mountains of Vermont, and the Berkshires of Massachusetts are readily accessible. Saratoga, with its battlefield, racetrack, and Performing Arts Center (New York City Ballet, Philadelphia Orchestra, and jazz festival) is nearby.

Application materials and information from:
Graduate Admissions
Rensselaer Polytechnic Institute
Troy, NY 12180-3590
Telephone: 518-276-6216
e-mail: admissions@rpi.edu
http://admissions.rpi.edu/graduate/

Faculty and Research Interests

Georges Belfort, belfor@rpi.edu
Membrane separations; adsorption; biocatalysis; M/RI; interfacial phenomena

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

Cynthia Collins, ccollins@rpi.edu
Systems biology; protein engineering; intercellular communication systems; synthetic microbial ecosystems

Marc-Olivier Coppens, coppens@rpi.edu
Nature-inspired chemical engineering; mathematical & computational modeling; statistical mechanics; nanoporous materials synthesis; reaction engineering

Steven M. Cramer, cramens@rpi.edu
Displacement, membrane and preparative chromatography; environmental research

Jonathan S. Dordick, Dordick@rpi.edu
Biochemical engineering; biocatalysis; polymer science; bioseparations

Shekhar Garde, garde@rpi.edu, Department Head
Macromolecular self-assembly, computer simulations, statistical thermodynamics of liquids, hydration phenomena

Ravi Kane, kaner@rpi.edu
Polymers; biosurfaces; biomaterials; nanomaterials, nanobiotechnology

Pankaj Karande, karanp@rpi.edu
Drug delivery; combinatorial chemistry; molecular modeling; high throughput screening

Lealon Martin, lealon@rpi.edu
Chemical and biological process modeling and design; optimization; systems engineering

Joel L. Plawsky, plawsky@rpi.edu
Electronic and photonic materials; interfacial phenomena; transport phenomena

Susan Sharfstein, sharfs@rpi.edu
Biochemical engineering, mammalian cell culture; recombinant protein production

Peter M. Tessier, terrier@rpi.edu
Protein-protein interactions, protein self-assembly and aggregation

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

Emeritus Faculty

Elmar R. Altwicker, altwic@rpi.edu
Spouted-bed combustion; incineration; trace pollutant kinetics

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

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

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

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

Peter C. Wayner, Jr., wayner@rpi.edu
Heat transfer; interfacial phenomena; porous materials
Chemical and Biomolecular Engineering @ Rice

The University

- Rice is a leading research university - small, private, and highly selective - distinguished by a collaborative, highly interdisciplinary culture.
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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 79 graduate students (72 Ph.D., 2 M.S., and 5 M.Ch.E.).
- 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

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- Inorganic/Organic Hybrids

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- Photonics & Optoelectronics
- Nanofabrication
- Display Technologies

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

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

Faculty

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

S. H. CHEN
Ph.D., Minnesota, 1981
polymer science, organic materials for photonics and electronics, liquid crystal and electrochromic displays

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

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

S. D. JACOBS
Ph.D., Rochester, 1975
optics, photonics, and optoelectronics, liquid crystals, magnetophotophysics

J. JORNE
Ph.D., California (Berkeley), 1972
electrochemical engineering, fuel cells, microelectronics processing, electrodeposition

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

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

C. W. TANG
Ph.D., Cornell, 1975
organic electronic devices, flat-panel display technology

J. H. DAVID WU
Ph.D., MIT., 1987
bone marrow tissue engineering, stem cell and lymphocyte cultures, enzymology of biomass energy process

H. YANG
Ph.D., Toronto, 1998
nanostructured materials, magnetic nano-composites, fuel cell electrocatalysts, ionic liquids, and bionanotechnology

M. Z. YATES
Ph.D., Texas, 1999
colloids and interfaces, supercritical fluids, microemulsions, molecular sieves, fuel cells

Chemical Engineering Graduate Studies

http://www.che.rochester.edu

Department of Chemical Engineering
University of Rochester
206 Gavett Hall
Rochester, NY 14627
(585) 275-4913
chegradinfo@che.rochester.edu

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The Chemical Engineering Department at Rowan University is housed in Henry M. Rowan Hall, a state-of-the-art, 95,000 sq. ft. multidisciplinary teaching and research space. An emphasis on project management and industrially relevant research prepares students for successful careers in high-tech fields. The new South Jersey Technology Center will provide further opportunities for student training in emerging technologies.

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Faculty

Robert P. Hesketh, Chair • University of Delaware
Kevin Dahm • Massachusetts Institute of Technology
Stephanie Farrell • New Jersey Institute of Technology
Zenaida Gephardt • University of Delaware
Mariano J. Savelski • University of Oklahoma
C. Stewart Slater • Rutgers University
Jennifer Vernengo • Drexel University

Research Areas

Membrane Separations • Pharmaceutical and Food Processing Technology • Biochemical Engineering • Biomaterials • Green Engineering • Controlled Release • Kinetic and Mechanistic Modeling of Complex Reaction Systems • Reaction Engineering • Novel Separation Processes • Process Design and Optimization • Particle Technology • Renewable Fuels • Lean Manufacturing Sustainable Design

For additional information

Dr. Jennifer Vernengo • Graduate Program Coordinator • Department of Chemical Engineering • Rowan University • 201 Mullica Hill Road • Glassboro, NJ 08028
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E-mail: vernengo@rowan.edu • Web: http://www.rowan.edu/open/colleges/engineering/
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The Department of Chemical Engineering at USC has emerged as one of the top teaching and research programs in the Southeast. Our program ranks in the top 20 nationally in research expenditures (> $6 million per year) and annual doctoral graduates. The Department offers Master’s 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.

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- **M.D. Amiridis**, Wisconsin  
  Catalysis and Kinetics
- **J. Blanchette**, Texas  
  Biomedical Engineering, drug delivery
- **C. Curtis**, Florida State  
  Vice provost for faculty development
- **F.A. Gadala-Maria**, Stanford  
  Rheology of suspensions
- **E.P. Gatzke**, Delaware  
  Modeling Control, Optimization
- **A. Heyden**, Hamburg  
  Computational Nanoscience, Catalysis
- **E. Jabbari**, Purdue  
  Biomedical and Tissue Engineering
- **M.A. Matthews**, Texas A&M  
  Applied Thermodynamics, Supercritical Fluids
- **M.A. Moss**, Kentucky  
  Protein Biophysics, Alzheimer’s Disease
- **H.J. Ploehn**, Princeton  
  Interfacial Phenomena, Nanotechnology
- **B.N. Popov**, Illinois  
  Electrochemical Power Sources
- **J.A. Ritter**, SUNY Buffalo  
  Separation and Energy Storage Processes
- **T.G. Stanford**, Michigan  
  Chemical Process Systems
- **V. Van Brunt**, Tennessee  
  Separations, Chemical Safety
- **J.W. Van Zee**, Texas A&M  
  Electrochemical Engineering, Fuel Cells
- **J.W. Weidner**, NC State  
  Electrochemical Engineering, Electrocatalysis
- **R.E. White**, Cal-Berkeley  
  Electrochemical Engineering, Modelling
- **C.T. Williams**, Purdue  
  Catalysis, Surface Spectroscopy

Contact us: The Graduate Coordinator, Department of Chemical Engineering, Swearingen Engineering Center, University of South Carolina, Columbia, SC 29208. Phone: 800.753.0527 or 803.777.1261. Fax: 803.777.0973. E-mail: chegrad@cec.sc.edu.  
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FACULTY

Dr. Venkat Bhethanabotla, Chair: Molecular dynamics, statistical mechanics, molecular thermodynamics, chemical and bio sensors

Dr. Norma A. Alcantar: Surface forces and chemical characterization, micellar surfactants, nanoparticles and organic/inorganic thin films

Dr. Scott W. Campbell: Phase equilibria, physical property measurement and correlation, monitoring and modeling of pollutants,

Dr. Richard Gilbert: Material science, biomedical systems, instrumentation, electrochemotherapy, electrogenetherapy, engineering education, and drug delivery

Dr. Yogi Goswami: Energy conversion, Solar energy, Hydrogen energy and fuel cells, Thermodynamics and heat transfer, HVAC

Dr. Vinay Gupta: Interfacial phenomena, polymers, self-assembly, molecular recognition, polymer adsorption, nanoscale/smart materials

Dr. Mark Jaroszeski: Drug and gene delivery, electrophoresis, biomedical instrumentation, electrophoresis

Dr. Babu Joseph: Modeling, simulation and control, sensor technologies, multi-scale modeling of systems, engineering education

Dr. John Kuhn: Catalysis, reaction engineering, material science

Dr. William E. Lee, PE: Biomechanics, human sensory perception, bioengineering, environmental biotechnology

Dr. J. A. Llewellyn: Artificial intelligence, modeling, data analysis, and educational computing

Dr. Carlos A. Smith, PE: Automatic process control, dynamic process modeling, process engineering

Dr. Aydin K. Sunol, PE: Systems engineering, process and product design, green engineering, supercritical fluid technology

Dr. Ryan Toomey: Materials science, polymer thin films, hydrogels, molecularly imprinted materials, and holographic polymerization

Dr. John Wiencek: Protein biophysics, novel membrane-based water purification

Dr. John Wolan: Advanced wide bandgap material systems, surface science, kinetics, fuel cells and solid-state sensors

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Department of Chemical & Biomedical Engineering
University of South Florida
4202 E. Fowler Avenue, ENB 118
Tampa, FL 33620
Phone: (813) 974-3997

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Rev: April 09
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Fax (931) 372-6352 • Also, visit us on the World Wide Web at: http://www.tntech.edu/che
Chemical Engineering graduate studies at the University of Texas at Austin are exciting, broad-based and interdisciplinary with faculty pursuing diverse research areas. We are one of the leading programs in chemical engineering excelling in all aspects of scholarship, research and education. Both M.S. and Ph.D. ChE degrees are offered. Fellowships and research assistantships, including stipends, tuition and fees, and medical insurance, are provided to qualified applicants.

Our Faculty

David T. Allen, Ph.D., Caltech, 1983
Hal S. Alper, Ph.D., M.I.T., 2006
Roger T. Bornecaze, Ph.D., Caltech, 1991
Lydia M. Contreras, Ph.D., Cornell U., 2008
James R. Chelikowsky, Ph.D., U of C. Berkeley, 1975
Thomas P. Edgar, Ph.D., Princeton U., 1971
John G. Ekerdt, Ph.D., U. of C. Berkeley, 1979
R. Bruce Eldridge, Ph.D., U. of Texas, 1986
Christopher J. Ellison, Ph.D., Northwestern U., 2005
Benny D. Freeman, Ph.D., U. of C. Berkeley, 1988
Venkat Ganesan, Ph.D., M.I.T., 1999
George Georgiou, Ph.D., Cornell U., 1987
Adam Heller, Ph.D., Hebrew U., 1961
Gyeong I. Hwang, Ph.D., Caltech, 1999
Keith P. Johnston, Ph.D., U. of Illinois, 1981

Brian A. Korgel, Ph.D., U. of C. Los Angeles, 1997
Douglas R. Lloyd, Ph.D., U. of Waterloo, 1977
Jennifer Maynard, Ph.D., U. of Texas, 2002
C. Buddie Mullins, Ph.D., Caltech, 1990
Donald R. Paul, Ph.D., U. of Wisconsin, 1965
Nicholas A. Peppas, Sc.D., M.I.T., 1973
Danny Reible, Ph.D., Caltech, 1982
Gary T. Rochelle, Ph.D., U. of C. Berkeley, 1977
Peter J. Rossky, Ph.D., Harvard U., 1978
Isaac C. Sanchez, Ph.D., U. of Delaware, 1969
Christine E. Schmidt, Ph.D., U. of Illinois, 1995
Mukul M. Sharma, Ph.D., U. of S. California, 1985
Thomas M. Truskett, Ph.D., Princeton U., 2001
C. Grant Willson, Ph.D., U. of C. Berkeley, 1973

Areas of study include:

- Biomedical and biochemical engineering
- Energy resources and sustainability
- Nanomaterials
- Surface phenomena and catalysis
- Polymers and polymer processing
- Meso- and molecular scale modeling and simulation
- Materials and processes for microelectronics
- Systems engineering, process control and optimization
- Air and water quality management

Address Inquiries to: Graduate Advisor • Department of Chemical Engineering • The University of Texas
1 University Station C0400 • Austin, TX 78712
Phone: 512/471-6991 • Fax: 512/475-7824 • utgrad@che.utexas.edu • www.che.utexas.edu
Texas Tech’s Chemical Engineering Graduate Program offers an outstanding balance between theory and experiment and between research and practice. The Faculty represents a broad range of backgrounds that bring industrial, national laboratory and academic experiences to the future graduate student. External funding supports a diverse research portfolio including Polymer Science, Rheology and Materials Science, Process Control and Optimization, Computational Fluid Dynamics, Molecular Modeling, Reaction Engineering, Bioengineering and Nanobiotechnology.

Key Features: We have thirteen faculty members with significant industrial experience and national recognition within their fields of expertise. There is a Process Control and Optimization Consortium with participation from eight key chemical industries. In 2005 the Department spent over $2.127 million in research expenditure to support graduate research projects. Based on an NSF published report, the Department ranks 46th among all the chemical engineering departments in the country based on research expenditure. Department has an NSF-funded Nanotechnology Interdisciplinary Research Team (NIRT) studying dynamic heterogeneity and the behavior of glass-forming materials at the nanoscale. More than 27,000 students attend classes in Lubbock on a 1,839 acre campus. Texas Tech University offers many cultural and entertainment programs, including nationally ranked football and basketball teams. Lubbock is a growing metropolitan city of more than 200,000 people and is located on top of the caprock on the South Plains of Texas. The city offers an upscale lifestyle that blends well with old fashioned Texas hospitality and Southwestern food and culture.

Admissions: Prospective students should provide official transcripts, official GRE General Test (verbal, quantitative written) scores, and should have a bachelor's degree in chemical engineering or equivalent. Students are urged to apply by the end of January for enrollment in the coming fall semester. Prospective students should apply online by filling out the forms at the graduate school website. www.depts.ttu.edu/gradschool/prospect.php
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 • che.utoledo.edu
cheedept@eng.utoledo.edu
Research Areas:
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Materials, Biomaterials, Colloids
Process Control
Reaction Kinetics, Catalysis
Energy and Environmental Engineering
Transport Phenomena

In 2000, Tufts became the first chemical engineering department in the nation to recognize the evolving interdisciplinary nature of the field by integrating biological engineering into its curriculum. Today, Tufts is nationally recognized for excellence in technological innovation, novel research, and superior faculty. Tufts offers ME, MS, and PhD degrees in chemical engineering or biotechnology engineering. Graduate students enjoy a broad arts and sciences environment with all the advantages of a research university, such as opportunities for interdisciplinary collaboration with the University’s leading medical and veterinary schools.

Department Faculty
Linda Abriola, Dean of School of Engineering Ph.D., Princeton University
Nak-Ho Sung, Department Chair Ph.D., M.I.T.
Gregory D. Botsaris Ph.D., M.I.T.
Aurelie Edwards 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
Kyongbum Lee Ph.D., M.I.T.
Steven Matson Ph.D., University of Pennsylvania
Jerry H. Meldon Ph.D., M.I.T.
William Moomaw, Ph.D., M.I.T.
Matthew Panzer, Ph.D., University of Minnesota
Blaine Pfeifer Ph.D., Stanford University
Daniel R. Ryder Ph.D., Worcester Polytechnic Institute
Howard Saltsburg Ph.D., Boston University
Ken Van Wormer Ph.D., M.I.T.
David Vinson Ph.D., Lehigh University
Hyunmin Yi Ph.D., University of Maryland

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The Department and its laboratories are housed in the Science & Technology Center, a state of the art research and teaching facility which also houses the cutting-edge interdisciplinary research activities of our Bioengineering Center.

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http://engineering.tufts.edu/chbe

For more information:
Tufts University
Chemical and Biological Engineering
Science & Technology Center
4 Colby Street, Room 148
Medford, MA 02155
Phone: 617-627-3900; Fax: 617-627-3991
E-mail: chbe@tufts.edu
Located in a vibrant international community just outside of Washington, D.C. and close to major national laboratories including the NIH, the FDA, the Army Research Laboratory, and NIST, the University of Maryland’s Department of Chemical and Biomolecular Engineering, part of the A. James Clark School of Engineering, offers educational opportunities leading to a Doctor of Philosophy or Master of Science degree in Chemical Engineering.

FACULTY

F. JOSEPH SCHORK, CHAIR
Polymer reaction engineering.

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/micro-fluidics, biophysics and numerical analysis.

SHERYL H. EHRMAN
Aerosol science; particle technology; air pollution.

JEFFERY KLAUDA
Cell membrane biophysics; thermodynamics; molecular simulations.

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

GANESH SRIRAM
Systems biology; metabolic engineering; bioenergetics; genetically inherited metabolic disorders.

CHUNSHENG WANG
Energy conversion for fuel cells; energy storage systems; sensors; electrochemistry; nanostructured materials.

NAM SUN WANG
Biochemical engineering; biofuels; drug delivery.

WILLIAM A. WEIGAND
Biochemical engineering; bioprocess control and optimization.

EVANGELOS ZAFIRIOU
Process control and optimization; systems biology.

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Research Areas:

For Information Contact:
Director of Graduate Studies
Department of Chemical and Biological Engineering
The University of Alabama
Box 870203
Tuscaloosa, AL 35487-0203
Phone: (205) 348-6450
Email: sritchie@eng.ua.edu
Web: http://che.eng.ua.edu

Faculty:
V. L. Acoff, Ph.D. (UAB)
G. C. April, Ph.D. (Louisiana State)
D. W. Arnold, PhD. (Purdue)
Y. Bao, Ph.D. (Washington)
C. S. Brazel, Ph.D. (Purdue)
E. S. Carlson, Ph.D. (Wyoming)
P. E. Clark, Ph.D. (Oklahoma State)
A. Gupta, Ph.D. (Stanford)
T. M. Klein, Ph.D. (NC State)
A. M. Lane, Ph.D. (Massachusetts)
S. M. Ritchie, Ph.D. (Kentucky)
C. H. Turner, Ph.D. (NC State)
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- **Energy and Environmental Applications**: hydrogen production, purification, and use in fuel cells
  
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- **Membranes and Separations**: tailored nanostructures
  
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- **Nanotechnology**: engineering of functional systems at the molecular scale
  
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- **Polymer Chemistry and Engineering**: chemical synthesis and applications of polymers and macromolecules
  
  K.S. Anseth; C.N. Bowman; S.J. Bryant; D.L. Gin; T.W. Randolph; J.W. Stansbury; M. Stoykovich

Kristi Anseth featured in the Popular Science Magazine article: The Brilliant 10 - November 2008
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FACULTY

Gary A. Aurand  
North Carolina State U. 1996  
Supercritical fluids/High pressure biochemical reactors

Greg Carmichael  
U. of Kentucky 1979  
Global change/Supercomputing/Air pollution modeling

Jennifer Fiegel  
Johns Hopkins 2004  
Drug delivery/Nano and microtechnology/Aerosols

C. Allan Guymon  
U. of Colorado 1997  
Polymer reaction engineering/UV curable coatings/Polymer liquid crystal composites

Stephen K. Hunter  
U. of Utah 1989  
Bioartificial organs/Microencapsulation technologies

Julie L.P. Jessop  
Michigan State U. 1999  
Polymers/Microolithography/Spectroscopy

David Murhammer  
U. of Houston 1989  
Insect cell culture/Bioreactor monitoring

Eric E. Nuxoll  
U. of Minnesota 2003  
Controlled release/microfabrication/drug delivery

Tonya L. Peeples  
Johns Hopkins 1994  
Bioremediation/Extremophile physiology/biocatalysis

C. Allan Guymon  
U. of Colorado 1997  
Polymer reaction engineering/UV curable coatings/Polymer liquid crystal composites

Alec B. Scranton  
Purdue U. 1990  
Photopolymerization/Reversible emulsifiers/Polymerization kinetics

Charles O. Stanier  
Carnegie Mellon University 2003  
Air pollution chemistry/measurement and modeling/Aerosols

Venkiteswaran Subramanian  
Indian Institute of Science 1978  
Biocatalysis/Metabolism/Gene expression/Fermentation/Protein purification/Biotechnology

For information and application:  
The University of Iowa  
Graduate Admissions  
Chemical and Biochemical Engineering  
4133 Seamans Center  
Iowa City IA 52242-1527  
1-800-553-IOWA  
chemeng@icaen.uiowa.edu  
www.engineering.uiowa.edu/~chemeng/
Chemical Engineering at the University of Michigan

Mark A. Burns, Chair • Microfluidics and Biochemical Analysis
Omolola Eniola-Adefeso • Cell Adhesion and Migration
H. Scott Fogler • Flow and Reaction
Sharon C. Glotzer • Computational Nanoscience and Soft Materials
Peter Green • Polymer Physics
Erdogan Gulati • DNA, Peptide Synthesis and Reactions at Interfaces
Jinsang Kim • Smart Functional Polymers
Nicholas Kotov • Nanomaterials, Biomaterials, Self-Organization Phenomena, 3D Tissue Engineering
Joerg Lahann • Biomaterials and Biointerfaces
Ronald G. Larson • Complex Fluids and Biological Macromolecules
Xiaoxia Lin • Systems and Synthetic Biology
Jennifer J. Linderman • Receptor Dynamics
Suljo Linic • Catalysis, Surface Chemistry and Fuel Cells
Michael Mayer • Biomembranes
Charles W. Monroe • Electrochemistry
Phillip E. Savage • Biocatalysis, Green Chemistry, Sustainability, Kinetics, and Mechanisms
Johannes W. Schwank • Catalysts, Fuel Cells, and Fuel Conversion
Max Shtein • Optoelectronic and Thermoelectric Materials, Devices, and Processing
Michael J. Solomon • Complex Fluids and Nanocolloids
Levi T. Thompson • Catalysts, Fuel Cells, and Microreactors
Angela Violi • Multiscale Computational Nanoscience
Henry Y. Wang • Bioprocess Engineering and Pharmaceutical Engineering
Peter J. Woolf • Systems Biology and Bioinformatics
Ralph T. Yang • Separations and New Materials for Energy/Environmental Applications
Robert M. Ziff • Nanostructures, Catalysis, and Modeling

For more information contact:
Department of Chemical Engineering
The University of Michigan
Ann Arbor, MI 48109-2136
734-763-1148
che-gradquestions@umich.edu
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### Faculty Research Areas

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<tr>
<th>Faculty</th>
<th>Research Areas</th>
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<tbody>
<tr>
<td>Plamen Atanassov</td>
<td>Electroanalytical Chemistry, Biomedical Engineering</td>
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<tr>
<td>C. Jeffrey Brinker</td>
<td>Ceramics, Sol-Gel Processing, Self-assembled Nanostructures</td>
</tr>
<tr>
<td>Heather Canavan</td>
<td>Stimulus-responsive materials, cell/surface interactions, Biomedical Engineering</td>
</tr>
<tr>
<td>Joseph L. Cecchi</td>
<td>Semiconductor Manufacturing Technology, Plasma Etching and Deposition</td>
</tr>
<tr>
<td>Eva Chi</td>
<td>Protein interfacial dynamics, protein aggregation, protein misfolding diseases</td>
</tr>
<tr>
<td>John G. Curro</td>
<td>Polymer Theory, Computational Modeling</td>
</tr>
<tr>
<td>Abhaya K. Datye</td>
<td>Catalysis, Interfaces, Advanced Materials</td>
</tr>
<tr>
<td>Elizabeth L. Dirk</td>
<td>Biomaterials, Tissue Engineering</td>
</tr>
<tr>
<td>Julia E. Fulghum</td>
<td>Surface Characterization, 3-D Materials Characterization</td>
</tr>
<tr>
<td>Steven Graves</td>
<td>Biomolecular Assemblies, Protease Mechanisms, Flow Cytometry</td>
</tr>
<tr>
<td>Sang M. Han</td>
<td>Semiconductor Manufacturing Technology, Plasma Etching and Deposition</td>
</tr>
<tr>
<td>Ronald E. Lochman</td>
<td>Glass-Metal and Ceramic-Metal Bonding and Interfacial Reactions</td>
</tr>
<tr>
<td>Gabriel P. López</td>
<td>Chemical Sensors, Hybrid Materials, Biotechnology, Interfacial Phenomena</td>
</tr>
<tr>
<td>Dimiter Petsev</td>
<td>Complex fluids, Nanoscience, Electrokinetic phenomena</td>
</tr>
<tr>
<td>Timothy L. Ward</td>
<td>Aerosol Materials Synthesis, Inorganic Membranes</td>
</tr>
<tr>
<td>David G. Whitten</td>
<td>Biosensors, Conjugated polymer photophysics and bioactivity in films and interfacial assemblies, Multicomponent systems and their applications</td>
</tr>
</tbody>
</table>

*For more information, contact:*
Sang Han, Graduate Advisor
Chemical and Nuclear Engineering • MSC01 1120 • The University of New Mexico • Albuquerque, NM 87131
505 277.5431 Phone • 505 277.5433 Fax • chne@unm.edu • www-chne.unm.edu
Research in the School of Chemical, Biological, and Materials Engineering (CBME) is characterized by INNOVATION AND IMPACT, leading to patents, technology licenses, spinoff companies and sought after graduates.

Research Areas

Bioengineering/Biomedical Engineering
Genetic engineering, protein production, bioseparations, vascular tissue engineering, cell adhesion, biosensors, orthopedic tissue engineering.

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

Materials Science and Engineering
Singlewall 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.

Faculty Members

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

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

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

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

Richard G. Mallinson
Ph.D. Purdue University, 1983

Peter S. McFetridge
Ph.D. University of Bath, United Kingdom, 2002

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

Edgar A. O’Rear, III
Ph.D. Rice University, 1981

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

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

David W. Schmidtke
Ph.D. University of Texas, Austin, 1980

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

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

Edgar A. O’Rear, Ill
Ph.D. Rice University, 1981

Alberto Striolo
Ph.D. University of Padova, Italy, 2002

For more information, e-mail, call, write or fax:
Chairman, Graduate Program Committee, School of Chemical, Biological and Materials Engineering, University of Oklahoma, T-335 Sarkeys Energy Center, 100 E. Boyd St., Norman, OK 73019-1004 USA
E-mail: chegrad@ou.edu
Phone: (405) 325-5811, (800) 601-9360
Fax: (405) 325-5813

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Tobias Baumgart Physical chemistry and mechanics of biological membranes, cell/surface interactions
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
David J. Graves Biochemical and biomedical engineering, biotechnology
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
Ravi Radhakrishnan Statistical mechanics, quantum chemistry, biomolecular and cellular signaling
Caslm A. Sarkar Biomolecular engineering, cellular engineering, biotechnology
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. Vohs 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 educational philosophy of the department reflects a commitment to continuing the Jeffersonian ideal of students and faculty as equal partners in the pursuit of knowledge.

Giorgio Carta, PhD, University of Delaware
Adsorption, ion exchange, protein chromatography, biochemical engineering

Robert J. Davis, PhD, Stanford University
Heterogeneous catalysis, reaction kinetics, conversion of renewable resources

Erik J. Fernandez, PhD, University of California, Berkeley
Purification and aggregation of protein therapeutics, molecular aspects of neurodegeneration

Roseanne M. Ford, PhD, University of Pennsylvania
Environmental remediation, microbial transport in porous media

David L. Green, PhD, University of Maryland, College Park
Reaction engineering of nanoparticles, rheology of complex nanoparticle suspensions.

John L. Hudson, PhD, Northwestern University
Engineering complex dynamics in reacting systems: applications to electrochemistry, biology, and medicine

Inchan Kwon, PhD, California Institute of Technology
Molecular and cellular engineering in biopharmaceutical, gene delivery and stem cell research

Steven McIntosh, PhD, University of Pennsylvania
Fuel cells, electrochemistry, advanced materials, heterogeneous catalysis

Matthew Neurock, PhD, University of Delaware
Molecular modeling, computational heterogeneous catalysis, kinetics of complex reaction systems

John P. O’Connell, PhD, University of California, Berkeley
Molecular theory, thermodynamic modeling and process simulation with applications to separations and hydrogen manufacture

Michael R. Shirts, PhD, Stanford University
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Materials and Interfaces
- Colloids and complex fluids
- Nanoscience/Nanotechnology
- Biomaterials and biointerfaces
- Electrochemical science and engineering

Molecular/Organic Electronics
- Organic solar cells
- Organic light emitting diodes
- Polymer physics
- Photonics

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- Stuart Adler (UC Berkeley)
- François Baneyx (Texas-Austin)
- John C. Berg (UC Berkeley)
- David G. Castner (UC Berkeley)
- Bradley R. Holt (Wisconsin)
- Thomas A. Horbett (Washington)
- Samson A. Jenekhe (Minnesota)
- Shaoyi Jiang (Cornell)
- Mary E. Lidstrom (Wisconsin)
- René M. Overney (Basel, Switzerland)
- W. Jim Pfandtner (Northwestern)
- Danilo Pozzo (Carnegie Mellon)
- Buddy D. Ratner (Brooklyn Poly.)
- N. Lawrence Ricker (UC Berkeley)
- Daniel T. Schwartz (UC Davis)
- Hong Shen (Cornell)
- Eric M. Stuwe (Stanford)

Graduate Admissions
Department of Chemical Engineering
University of Washington
Seattle, Washington 98195-1750
Phone: 206-543-2250
Fax: 206-543-3778

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Edward J. Kramer, NAE
L. Gary Leal, NAE
Glenn E. Lucas
Eric McFarland
Samir Mitragotri
Baron G. Peters
Susannah L. Scott
Dale E. Seborg
M. Scott Shell
Todd M. Squires
Theofanis G. Theofanous, NAE
Matthew V. Tirrell, NAE
Joseph A. Zasadzinski

Affiliated faculty

Song-I Han
George M. (Bud) Homsy, NAE

Research strengths

Biomaterials and bioengineering
Catalysis and energy
Complex fluids and polymers
Electronic and optical materials
Fluids and transport
Process systems engineering
Surfaces and thin films

Interdisciplinary research

California Nanosystems Institute
Center for Control Engineering
and Computation
Center for Polymers and Organic Solids
Center for Risk Studies and Safety
Institute for Collaborative Biotechnologies
Institute for Energy Efficiency
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Jennifer Sinclair Curtis
Richard B. Dickinson
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Anthony J. Ladd
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- Biomolecular and Cellular Engineering
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- Reaction and Separations Engineering
- Transport Processes
- Advanced Materials Technology
- Electronic and Photonic Materials
- Nanotechnology
- Systems and Control
- Gene Medicine

Faculty

Andrea M. Armani (Caltech)
Edward Goo (Stanford)
Rajiv K. Kalia (Northwestern)
Noah Malmstadt (Washington)
S. Joe Qin (Maryland)
Katherine Shing (Cornell)
Pin Wang (Caltech)
W. Victor Chang (Caltech)
Malancha Gupta (MIT)
C. Ted Lee, Jr. (Texas-Austin)
Florian Mansfeld (Univ. of Munich)
Richard W. Roberts (Yale)
Theodore T. Tsotsis (Illinois-Urbana)
Yannis C. Yortsos (Caltech)
Iraj Ershaghi (Univ. of Southern Calif.)
Kristian Jessen (Tech. Univ. of Denmark)
Anupam Madhukar (Caltech)
Steven R. Nutt (Virginia)
Muhammad Sahimi (Minnesota)
Priya Vashishta (IIT-Kanpur)
Dongxiao Zhang (Arizona)

Faculty with Joint Appointments

Edward D. Crandall [Medicine] (Ph.D., Northwestern; M.D., Pennsylvania)
Martin Gundersen [Electrical Eng] (Univ. of Southern Calif)
Michael Kassner [Aerospace & Mechanical Eng] (Stanford)
Aiichiro Nakano [Computer Science] (Univ of Tokyo)
Armand R. Tanguay [Electrical Eng] (Yale)
Chongwu Zhou [Electrical Eng] (Yale)
P. Daniel Dapkus [Electrical Eng] (Illinois-Urbana)
Andrea Hodge [Aerospace & Mechanical Eng] (Northwestern)
Terence G. Langdon [Aerospace & Mechanical Eng] (Univ of London)
George A. Olah [Chemistry] (Tech. Univ. of Budapest)
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For more information:
Director of Graduate Studies
Department of Chemical and Biomolecular Engineering
Vanderbilt University • VU Station B 351604
Nashville, TN 37235-1604
Email: chegrad@vanderbilt.edu
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

Christopher J. Cornelius (Virginia Tech)
Hybrid organic-inorganic materials, sol-gel chemistry, self-assembly

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

Erdogan Kiran (Princeton)
Supercritical fluids, polymer science, high pressure techniques

Y.A. Liu (Princeton)
Pollution prevention and computer-aided design

Eva Marand (Massachusetts)
Transport through polymer membranes, advanced materials for separations

Stephen M. Martin (Minnesota)
Soft materials, self-assembly, interfaces

Abby W. Morgan (Illinois)
Tissue engineering, controlled release of proteins

S. Ted Oyama (Stanford)
Heterogeneous catalysis and new materials

Padma Rajagopalan (Brown)
Polymeric biomaterials, cell and tissue engineering

John Y. Walz [Dept. Head] (Carnegie Mellon)
Colloidal stability, interparticle forces

For further information write or call the director of graduate studies or visit our webpage
Department of Chemical Engineering
133 Randolph Hall, Virginia Tech, Blacksburg VA 24061
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Ralph Kummler, (Dean of Engineering) Ph.D., John Hopkins • modeling of sewer flows and sediments; chemical kinetics; air pollution control; hazardous waste management.

Joseph Louvar, Ph.D., Wayne State • chemical process safety; shortstopping runaway reactions via CFD models; characterizing runaway reactions.

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Steven Salley, Ph.D., U of Detroit • biochemical / biomedical engineering; materials for medical applications.

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Contact: Department of Chemical Engineering and Materials Science, Wayne State University, 5050 Anthony Wayne Dr., Detroit, MI 48202 • Phone: 313-577-3800 / 3837 • chegrad@eng.wayne.edu

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Faculty

Sushant Agarwal
West Virginia University

Brian J. Anderson
Massachusetts Institute of Technology

Eung H. Cho
University of Utah

Eugene V. Cilento, Dean
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Professor Brian Anderson
Graduate Admission Committee
Department of Chemical Engineering
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West Virginia University
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For more information, please contact:
Graduate Program Office
Department of Chemical & Biological Engineering
University of Wisconsin–Madison
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