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LEARNING IN INDUSTRY
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The following is the first BSL Lecture, given at the University of Wisconsin on October 2, 2001.

THE EQUATIONS (OF CHANGE) DON'T CHANGE
But the Profession of Engineering Does

W. R. SCHOWALTER
University of Illinois at Urbana-Champaign • Urbana, IL 61801

At the outset, I wish to express my thanks for the honor to be associated with this celebration marking the appearance of the 2nd edition of *Transport Phenomena*. The enormous influence of the first edition on chemical engineering education is so obvious and well known that it would be gratuitous for me to spend time talking about how the book transformed chemical engineering education throughout the world. That is not to say its adoption was immediate or uniform across the country. Similar to Feynman’s *Lectures on Physics*, the instructors often learned more than the students. With apologies for the terribly mixed metaphors, one could describe BSL as a stew that didn’t always fly well with lightweight.

This talk is meant to be forward-looking rather than backward-reminiscing, but it is clear that included in my qualifications for delivering this lecture are (a) my pedigree as an alumnus of this department and (b) a date of birth that puts me in an ever-contracting pool of candidates who were educated in pre-BSL history. I therefore choose a few preliminary stories, which (beyond being amusing) have, I hope, some value as reminders of the reach and the lasting influence, often unintended, those of us who teach have on a large body of students.

- Until late in my undergraduate experience, the most influential instructors I had were, with one exception, graduate students. Names such as Ednie, Garver, Woods, and Kirk come to mind. Bob Kirk was an assistant professor. The others were instructors and World War II veterans, several of them married with young families. They were no-nonsense people who took their teaching duties seriously and, for the most part, explained the material well. There is a lesson in this bit of history. In spite of our recoil when we are told that students are forced to learn from graduate students rather than senior faculty, instruction from graduate students isn’t necessarily a bad experience. In fact, it has the advantage of being taught by someone more apt to appreciate student difficulties, often similar to those endured just a few years earlier by the instructor, than is the case when a full professor is in charge.

The “big names” in the department in those days were Hougen and Marshall. As an undergraduate, I had no contact whatsoever with either one. In later years, however, I came to know both gentlemen well—Bob Marshall through AIChE committees and Olaf Hougen when he joined a Madison retirement center to which my parents had moved. He was a truly remarkable person.

- The second vignette has to do with undergraduate advising. In my sophomore year I became frustrated because it seemed all I was doing was rushing from one assignment and exam to another, without time to reflect on what I was learning. I went to my adviser, Professor C.C. Watson, and told William R. Schowalter, professor and dean emeritus of the College of Engineering at the University of Illinois at Urbana-Champaign, is currently senior advisor to the president of the National University of Singapore. He received his BS from the University of Wisconsin, and his MS and PhD from the University of Illinois, all in chemical engineering. He is an authority in the field of fluid mechanics, especially as it applies to the processing of polymer melts, polymer solutions, and colloidal dispersions.
him I wanted to cut back on the number of courses and stretch out my residence time to five years. He looked at my grades, then looked at me, and said there was no reason for me to take longer than four years. His answer was no—end of discussion, end of appointment with adviser. Years later I could say with conviction that his decision was absolutely correct. I can only guess why he refused me, but I suspect he believed I would use the extra time for anything but “reflecting” on what I was learning, and I was probably too immature to know what to reflect about. Beyond that, one needs a balance between thoroughness and efficiency. Part of engineering education is learning how to find that balance.

AN OVERVIEW

Engineering education is, by its very nature, in a continuous state of flux. Appearance every decade of a definitive report on the future of engineering education is as predictable as a sighting of the first crocuses in Madison near the end of March. The constant uncertainty over what we teach should not be surprising. Engineers solve problems. If they are successful, those problems disappear. Then we find new problems to solve. Although the principles used to solve successive generations of problems change very slowly, the problems themselves have different emphases and different details that require continual fine tuning, and, as with BSL, occasional step changes in our approaches.

In my remarks, I shall first offer comments on the purpose of undergraduate engineering education within the context of a large, selective university such as UW Madison. From there I wish to specialize the discussion to challenges and opportunities relevant to chemical engineering departments within such institutions, looking successively at undergraduate, professional, and graduate (PhD) curricula. Finally, a few generalizations are offered regarding challenges for comprehensive public research universities.

UNDERGRADUATE EDUCATION

A popular current claim of engineering educators, and one to which I subscribe, is that our subject is the liberating art of the 21st century. That claim lays upon the departments making it a set of curricular responsibilities which, I believe, includes

1) A program of study sufficient for entry-level positions in engineering practice and engineering-related fields
2) Exposure to “shoulder areas” of engineering
3) Provision for an understanding of professional and personal ethics
4) Mastery of fundamentals sufficient to pursue graduate study in engineering or related fields

These features of an undergraduate engineering education are not without controversy, so I should explain why I believe they are important and valid.

First, we are not in the business of providing solely a “pre-professional” education, in spite of the efforts of generations of educators to do so. The educators have failed because the market has dictated otherwise. In good economic times, eager companies line up at the nation’s best engineering schools to nab graduates of four-year accredited programs. Sometimes those graduates enter highly focused technical areas in the electronics, chemical, or automotive industries, and they will probably receive a generous dose of in-house training to sharpen the generalities learned in their BS education. Nevertheless, they are hired as engineering graduates, not as products of a generalized pre-engineering curriculum now ready for finishing school. Alternatively, other companies are anxious to hire them for jobs in which the analytical and reasoning skills of the graduates will be applied to a broad rather than narrow and highly disciplinary context. During the past decade, the consulting firm Accenture has been one of the largest employers of entry-level engineers graduating with a four-year BS degree from Illinois.

Second. I refer above to the “shoulder areas” of engineering. This is an acknowledgment of the fact that engineering is a profession that cannot be practiced in isolation—it requires a context. Here is where the “liberating art” label can be argued. As technology forms an ever-deepening influence on the lives of everyone, it should be expected that an education in engineering must provide a foundation for future specialization in business, law, or (as we are beginning to see) even the arts. Those connections should not be left to chance. On the contrary, opportunities to link strictly technical issues with economic, social, and political factors should be sought and exploited. Note that this implies more than a simple requirement for students to take x credits of subject y during their undergraduate education.

The third ingredient referred to pertains to professional and personal ethics. If an engineering education does not help us to understand and promote a civilized society, it is not a liberating art. Again, this emphasizes that engineering is practiced in a context. Precisely because engineering is so important in today’s world, a so-called “engineering decision” is seldom without consequences far beyond the realm of engineering itself. Those decisions have far-reaching economic, social, and ethical implications, and the choices among alternatives are seldom clearly right or clearly wrong.
Fourth. I have required that an undergraduate curriculum properly serve the person who wishes to compete at the highest level in graduate study in engineering or a related field. This is the true proof of principle when we claim to be educating engineers. It separates the schools preparing engineers from the schools preparing dilettantes. My opinions here have been shaped by many years on the faculty at Princeton. At that institution, the largest number of undergraduate majors over a period of several decades were in either English or history. Clearly, very few of those majors went on to make a living in either of those fields. Some did, however, and they became distinguished in their specialty. We should be able to do the same. It is not necessary for a school of engineering to choose between producing either specialists or persons so well-rounded they have no peaks of excellence.

I have laid out a daunting assignment for an undergraduate engineering program. How can one provide the technical depth required to excel at subsequent graduate courses in fast-moving fields, while at the same time give proper attention to the shoulder areas and general intellectual maturation implied in the above remarks? Let me be the first to admit that it is not easy, and it is probably not possible for any but the most selective of institutions. To accomplish the ends stated here, one needs entering students with a rare combination of mental ability, preparation, and maturity. Those young people surely exist in our society. It is up to the engineering profession to convince them that study of engineering is worth their attention. It is when we do not attract a sufficient number of these students that we say the curriculum is too difficult, too stuffed with requirements for completion in four years, or too boring. I should add that this can become a vicious circle. It is possible to design a curriculum with all of these undesirable features—one that will dissuade from the outset attracting the type of students we wish to see.

### CHEMICAL ENGINEERING

**Undergraduate Education**

Everything said so far pertains to all of engineering. What can one say that is unique to chemical engineering? This is, in fact, becoming an increasingly difficult question to answer—especially at the graduate level, as we shall see shortly. There are some distinguishing, if not unique, features of chemical engineering practice and education, however. For the moment, let us concentrate on ramifications for undergraduate education. I believe we distinguish ourselves through the following three characteristics:

- A focus on chemical change
- Well-developed methodologies for describing separation of mixtures into their components
- A systems approach to the design and description of processes

These three features can be expanded as shown in Figure 1. Will these characteristics ensure a healthy chemical engineering profession into the next generation? In my opinion, they will not, because we have forgotten a critically important ingredient: the student. More than anything, a preponderance of high-quality students has sustained us ever since World War II. We have operated more-or-less successfully under the paradigm, “Build a sound curriculum, and they will come.” I don’t believe that approach will work in the future. In order to engage the cream of the student body, we need to educate students who, upon graduation, will find jobs with satisfactory financial compensation, intellectual challenge (something that really is rocket science), and a sense of excitement and mission, i.e., conviction that one’s work will make the world a better place.

How do we measure up? Relative to other engineering disciplines, job opportunities for chemical engineers have been plentiful, if not as legendary as they were for several years in computer engineering and science. On the criterion of intellectual challenge, we measure up very well indeed. We teach fundamental reasoning rather than rote application of facts, and students are stretched accordingly. It is with respect to the last item on the list that we fall short. Faculty members are excited about what they are doing, but the number of links in a chain of inference between that excitement and the excitements of engineering practice is perilously large. This is not true with engineering in general. It happened in our field because the interests of faculty members and the needs of practitioners have diverged. Such does not have to be the case if one is to retain the intellectual challenge of the second point.

As an example, I have compared in Table 1 the citations of some academics recently elected to the National Academy of Engineering in the chemical engineering section (Section 3) and the electronics engineering section (Section 7). I believe one finds a much closer identification of the latter group with the current interests and proclaimed needs of the industry they represent. Nevertheless, they are presumably conducting re-
search considered by their peers to be at the highest level among their cohorts. I don’t mean to imply a value judgment by the comparison, but our profession is at some risk when there is lack of identification with the areas of commerce we claim to serve. The link between academic research and commercial needs is much stronger in the bio-related areas of chemical engineering, and that is one reason for the current vitality of that subject.

It is universally agreed that bioengineering, biotechnology, and bioscience are important to the future of chemical engineering. Exactly how that importance is to be acknowledged in our curricula and research is still an open question, and indeed, there is no single answer. Pluralism has been a pillar of strength for the U.S. educational system, and we shall no doubt see many successful models. Before leaving this subject, I do wish to provide an often-forgotten historical perspective. Fifty years ago, programs in biochemical engineering, or its equivalent, already existed at Wisconsin and Illinois, and probably at other schools as well. I do not believe any of them had a large following. Timing is everything!

Bioengineering is not the only cross-cutting subject on which chemical engineering should have an important influence. An emphasis on chemical change implies a special interest and competence in things at the molecular and near-molecular length scale, a current area of great promise in technology. At the other end of the length scale are macro-projects associated with a systems approach. Although chemical engineering education has profited from its close-knit structure, perhaps the time has come to consider multiple tracks to a degree, an approach successfully followed for decades by electrical engineers.

**Professional Education** • I will say the least about this because here, for the most part, chemical engineering departments are involved at the margins. Put differently, if we excelled in this arena, the profession would benefit but the impact would not be overwhelming. Likewise, if we turn our backs on professional education, the damage done is not life threatening to our profession or to the universities. To a large extent, one can say this because other stakeholders have a firm grasp on professional education: the professional societies, private firms, and the internal education programs of most large technology companies.

Having said that, I believe there are significant opportunities for universities to gain from professional education initiatives. Stanford is probably the most outstanding example. Its electrical engineering and computer science departments and the technology culture in the Palo Alto area have been inseparable. From that example as well as others, distinct advantages for an academic department and its inhabitants include:

- **Discretionary income for the providing unit** (a for-profit venture)
- **Opportunity for faculty members to be closer to the firing line** (see above criticism aimed at many chemical engineering departments)
- **A chance for students and practitioners to mingle**

**TABLE 1**

<table>
<thead>
<tr>
<th>Chemical Engineering Section</th>
<th>Electronics Engineering Section</th>
</tr>
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<tbody>
<tr>
<td>For advancing our understanding of the behavior of block copolymers and other polymeric and complex fluids</td>
<td>For advances in optoelectronic devices, detectors for fiber optics, and efficient LEDs for displays</td>
</tr>
<tr>
<td>For advancing our understanding of electrokinetic and electrohydrodynamic processes . . .</td>
<td>For contributions to the development of CMOS technology . . .</td>
</tr>
<tr>
<td>For pioneering contributions in defining and advancing metabolic engineering . . .</td>
<td>For contributions to signal and image processing . . .</td>
</tr>
<tr>
<td>For advancing our understanding of the mechanisms and modeling of processes that control radiation in and pollutant control of combustors</td>
<td>For contributions to and leadership in research on microelectromechanical systems</td>
</tr>
<tr>
<td>For elucidating the flow properties of complex fluids at the molecular and continuum levels . . .</td>
<td>For introducing photonic band-gap engineering and applying semiconductor concepts to electromagnetic waves in artificial periodic structures</td>
</tr>
</tbody>
</table>

For elucidating the flow properties of complex fluids at the molecular and continuum levels . . .
The MIT Practice School. This venerable program, also leading to a Master’s degree, has been in existence for generations and is arguably the most influential and effective of all advanced work-study programs.

These examples indicate that it is possible for professionally oriented education to be both financially and intellectually rewarding for chemical engineering departments. Issues of resource allocation, faculty interest and talent, and geography, however, all indicate a local decision on the importance of a professional education component to a department’s welfare.

Graduate Education • This is the arena that has the deepest effect on faculty careers at a research-oriented university such as Wisconsin. Research funding, publications, graduate students, and professional advancement and rewards all hinge on graduate education. It is also the arena where, I believe, the distinctiveness of chemical engineering is rapidly disappearing—as is the distinctiveness of any brand of engineering. We are witnessing a secularization of the disciplines of engineering. When I was a Wisconsin undergraduate, the auto industry held sway over mechanical engineers. The atrium of the Mechanical Engineering Building was decorated with a huge banner hanging from the ceiling and proclaiming the latest doings of the Society of Automotive Engineers. Electrical engineering graduates went to work for Wisconsin Electric Power or one of the electronics companies that at that time had a high concentration in the Midwest (if I remember correctly, names such as Zenith, Haseltine, and Collins were prominent), and chemical engineers worked for chemical or petroleum companies, with a local emphasis on the paper industry. Contrast that with today: ME’s design disk drives, ChE’s work on prosthetic devices, and EE’s work on just about everything.

These examples are drawn primarily from the BS/MS levels, but it is perhaps even more evident at the PhD level. By probing more deeply into our sub-specialties, we have gone our separate ways, a bit like swimming through fish traps of ever-narrower pore size, and now we are finding ourselves all in the same large trap. It has the name “bio/info/nano.” As a consequence, we are entering a period of great excitement and opportunity at the frontiers of knowledge. It is a development we should welcome rather than fear, but it does pose challenges for our system of doctoral education. I make no claim to having all the prescriptions for meeting those challenges, but I do have some suggestions.

To look for some answers, I recently sought advice from a colleague, Michael Heath, in our Department of Computer Science. Mike is director of a large DOE-sponsored effort housed in the Center for the Simulation of Advanced Rockets (CSAR) and known as the Accelerated Strategic Computing Initiative (ASCI). The mission of CSAR is to simulate the behavior of rockets from a systems point-of-view, meaning the problem involves issues of mechanics, combustion, materials, and aerodynamics. Specific thrust areas are the province of faculty members from departments of physics and most of the departments of engineering at Illinois.

Mike, whose own specialty is scientific computing, describes the work of the Center as “nonlinear everything.” I asked him how it was possible to make rational progress when everything depends on everything. His response was not surprising. He stressed the importance of a tight network for efficient and multichannel communication. It is imperative that people talk with, listen to, and understand each other. This requires effort on all sides. The materials people need to appreciate the problems of the propulsion people, who in turn need to know the problems and constraints of the guidance and control people, etc. There must also be an overall goal and periodic evaluations of how the group is reaching that goal. As we talked, I gained a new appreciation for the importance on our campuses of interdepartmental laboratories, centers, and institutes. They have become more than desirable—they are now essential.

I conclude from these experiences that research themes must go beyond the “Professor X group” mentality and that interpenetration among groups must be real and substantial. This means that PhD research will need to be “managed” more effectively than before. Perhaps more of the funding for our research should be structured along the lines of NIH and be project- or goal-oriented, as are most of the individual institutes of NIH. There has been periodic discussion of a similar structure for NSF, but to the best of my knowledge, serious consideration has not taken place.

In Table 2 I have shown a balance sheet for task-oriented research conducted with graduate students. The capability to be technically multilingual and to work in cross-functional groups is a skill deemed critical to survival in contemporary professional life, and the sooner students become adept at it, the more valuable their service will be to an employer. This, by the way, is no less true in academe than in industry. The reason for this added-value is, of course, because most important problems today cannot be solved in isolation. Mike

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>Some Consequences of Task-Oriented Research</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Assets</strong></td>
<td><strong>Liabilities</strong></td>
</tr>
<tr>
<td>Students (and faculty!) become technically multilingual</td>
<td>More difficult to do academic administration</td>
</tr>
<tr>
<td>Solutions to important research problems are more likely to be found</td>
<td>Disciplinary core can become an endangered species</td>
</tr>
<tr>
<td>Silo mentality is neutralized</td>
<td>Unclear lines of reporting and responsibility for junior faculty members</td>
</tr>
<tr>
<td>Attractive research topics for students</td>
<td>Residence time to degree can increase</td>
</tr>
</tbody>
</table>
Heath’s “nonlinear everything” applies far beyond CSAR. Working against the assets of Table 2 are the potential liabilities. Note, however, that with the possible exception of the second item, the liabilities are driven by structure rather than by substance. That is not to claim that alteration of a structure is a simple matter, or that the present structure does not serve a purpose. Overcoming the challenges posed in the liabilities column is perhaps the major task today of the graduate schools of the major research universities.

There is an additional contemporary issue not identified in Table 2. Few will deny that our nation’s research capability has been put at risk by the demise of most of our major industrial research laboratories. In the past, they often carried out the important task-oriented but fundamental engineering research essential to a technically advanced civilization’s technology base. Much of that research has now been transplanted to university campuses. But if corporate shareholders are unwilling to pay for these admittedly necessary results, who should? The federal government? A consortium of federal governments? (The European Union represents one model of the latter.) This is a question that deserves a better answer than either industry or government has provided to date. A step in the right direction would be clearer articulation by government research-supporting agencies of the relative importance to them of research results and the advanced education of graduate students.

THE COMPREHENSIVE PUBLIC RESEARCH UNIVERSITY

Moving to the final item on my agenda, we must not forget that chemical engineering education is often conducted within the environment of a research university, which itself is a dynamic institution. Much has been written about the shape of research universities in the future, the increasing role of corporate and philanthropic support, and the need to preserve excellence in subjects not directly related to economic needs. For a more global view than is appropriate here, I refer you to a recent book[3] by James Duderstadt, an engineer and former president of the University of Michigan.

I do wish to voice a somewhat parochial concern about universities such as Wisconsin and Illinois, and that is the ever-widening gap in resources between the top-tier private and the top-tier public research universities in this country. The former had extraordinary endowment growth during the 1990s. That growth will, of course, erode in down-markets, but the miracle of compound interest is such that I fear the public will never catch up.

A few years ago, Illinois made a comparison of faculty salaries at different ranks among leading public and private universities. The most dramatic result of this comparison was a shift that has occurred during the past twenty years. Twenty years ago there was a healthy mix of publics and privates among the top performers. Today, private institutions dominate those providing the highest faculty salaries. Salaries, of course, do not alone reflect the quality of a research university, but they are, over time, an important indicator.

Midwestern universities, in particular, need to reaffirm their desire to compete with the best and to convince their citizens of the value these universities add to their states. We need a new articulation of the land-grant idea, probably in a concerted way across several states. This is too large an issue to be appropriate for more than a passing comment in a talk of this type, but it will surely affect chemical engineering education at universities such as ours.

So what does all of this mean for Transport Phenomena II and the University of Wisconsin’s place in the history of chemical engineering education? The clear and illuminating developments of momentum, energy, and mass transfer found in Transport Phenomena I are intact in the second edition. Those concepts and the tight coupling between them will surely remain in what we consider the chemical engineering canon. But people toting the successor to that familiar red (or in later printings, green) classic must find applications we haven’t dreamed of. If they don’t, chemical engineering will deserve to be devoid of bright, ambitious, competitive, and interesting students. My own bet will be on the side of a future in which Transport Phenomena II will follow its own laws of diffusion. The subject will penetrate into new areas of application and enrich them, and it will be students educated through Transport Phenomena II who will be the agents of change for diffusion of the subject into the broad sweep of modern technology.

SUPPLEMENTARY READING

5. Servos, John W., “The Industrial Relations of Science: Chemical Engineering at MIT, 1900-1939,” Isis, 71, 531 (1980)
MIXING WRITING WITH FIRST-YEAR ENGINEERING
An Unstable Solution?

LISA LEBDUSKA, DAVID DIBIASIO
Worcester Polytechnic Institute • Worcester, MA 01609

Most first-year students have little in-depth knowledge of their chosen profession—particularly in engineering, which has so few high school experiences connected to it. Moreover, chemical engineering departments rarely offer core courses until the sophomore year and hence have little contact with first-year students interested in chemical engineering. Recently, more departments have begun offering seminars or other career-oriented activities for first-year students, recognizing that early engagement with the profession can increase motivation for learning and improve retention in the major. Improving student understanding of engineering should certainly allow students to make informed, rational decisions about their academic and professional careers, but providing them with such an understanding can be challenging and too often devolves into passive activities such as seminars and introductory technical courses. By contrast, a process that engages students actively in learning about and identifying with engineering would benefit both them and the profession.

Students’ ability to identify with their chosen profession improves both motivation for learning and retention in the major and also seems to influence their ability to write effectively. Science writing is often influenced by “a student’s inadequate sense of self as scientist,” and a similar rhetorical struggle would be expected for students in engineering disciplines. If engineering students do not view themselves as engineers, they cannot become fully aware of the audience to which they are writing and the specific needs of that audience. Consequently, they approach engineering writing without adequate knowledge of the language practices that define their discipline. Traditional writing assignments such as lab write-ups, while helpful in shaping students’ thinking and identifying what is new knowledge to them, may not help them adopt professional roles. Lab reports typically are written to document completion and understanding of the engineering process. For the most part (and with good reason), first-year labs do not ask students to write as professionals but as novices demonstrating skills and knowledge.

Educators have addressed engineering students’ writing abilities for over a hundred years, with varying degrees of success and satisfaction. Institutions have adopted a range of approaches to improve students’ writing skills, such as writing-across-the-curriculum (WAC) courses that integrate technical content with rhetorical analysis. Despite good intentions, however, some of these WAC approaches have nevertheless failed to adequately prepare engineering students for the types of writing tasks that they will encounter academically and in their careers. As technologists and humanists often use different techniques to teach writing, it may be difficult for students to incorporate lessons from the humanities into their engineering coursework. Engineers may also lack the language and understanding of composition studies to effectively teach the writing process. Offering a pedagogical balance between engineering and rhetoric is thus a challenging problem.

At Rensselaer Polytechnic Institute, the chemistry department employed writing consultants from the Department of

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Language, Literature, and Communication to work with junior-level chemistry majors on their lab reports in two required "writing intensive" courses. These consultants met with chemistry faculty to discuss writing practices in that discipline before they began offering feedback to students, who produced multiple drafts of their reports before submitting final versions for grading. The writing focus in this WAC effort targeted upper-class students and formal lab writing and resulted in better quality lab reports. A WAC effort in the Department of Animal Sciences at the University of Kentucky similarly targeted upper-class students through a senior-level course, but by contrast it emphasized more "real world" assignments that would help students recognize the importance of writing in their discipline—an achievement that is often sought by WAC endeavors in engineering and technical programs. The Kentucky course stressed the importance of rhetorical context in writing assignments to improve student interest and to clarify assignment objectives.

A much broader, more programmatic approach to WAC has been undertaken by the Materials Science and Engineering Department at Virginia Polytechnic Institute, which integrates writing and speaking into eight core courses that students take over a three-year period. The sequence used a combination of formal and informal ("interpersonal") communication assignments, peer writing consultants, and supplemental writing workshops. Their efforts seem to have contributed to the establishment of a required zero-credit class for majors that asks students to create a writing portfolio containing their best work in a variety of modes from their required classes.

Historically, attempts to understand these varying approaches to writing have resulted in two groups: in one, the expressivist model, writing is used as a means of teaching and learning, employing free writing and journals, and in the other, the "social constructionist model," writing pedagogy emphasizes disciplinary or workplace conventions. Such categorization oversimplifies the WAC process, with some researchers turning to an "interactionalist" approach that combines elements of both models. "An interactional approach...emphasizes that learning is a social process that necessitates active involvement on the part of both the learner and the teacher while also emphasizing the contribution of disciplinary knowledge in the transaction."

At WPI, we attempted to adopt a scaled-down version of this "interactionalist" approach, which had been developed through a successful collaboration between humanities and engineering faculty at Michigan Tech University. Our interactionalist approach involved using some writing activities that taught students to use writing as a means of understanding what they wanted to say and were exploratory. Other activities, by contrast, introduced them to conventions within the discipline and encouraged them to learn and reproduce those conventions. The balance, in part, is between teaching students what they need to learn to become practitioners of an inherited discourse while also giving them the critical thinking skills they need to question and challenge conventions. Leadership in any field requires individuals who can go beyond the mere reproduction of knowledge by continually reexamining the discipline and, when needed, reshaping it.

**COURSE OBJECTIVES**

Students often think of writing and speaking strictly in terms of evaluation, e.g., the lab report or presentation that they must produce to "prove" that they completed and understood the science. They have a fairly limited understanding of what "communication" can be used for. At the same time, their knowledge of what chemical engineers actually do is equally limited. Because WPI does not offer freshman chemical engineering courses or require writing courses, we wanted to design a course that would actively engage students in the profession while improving their approach to and understanding of communication as a problem-solving tool. Additionally, we needed to recognize that although first-year chemical engineering majors do not take any chemical engineering courses, they carry one of the heaviest academic course loads on campus, a fact that challenged us to design a one-credit class that would achieve our pedagogical goals but still attract students.

**THE APPROACH**

Jointly taught by a chemical engineering professor and a writing professor, the course stressed collaboration between chemical engineering and communication in its design and its execution. We reasoned that the best way to teach that communication and chemical engineering should inform each other was to demonstrate the integration, so we collaborated on the design and delivery of every assignment. Both instructors attended every class, so the students would again see the connection between the two disciplines and not think of "communication days" versus "chemical engineering days."
Course development was funded through a WPI grant (itself supported by NSF’s Institute-Wide Reform Program) the first year and a Davis Educational Foundation grant the second year.

We offered the course three times over two academic years, revising it after each offering. About one-third of the declared majors took the course each offering (7-10 students per semester). We required portfolios each time we taught the course, but in the second offering we required the students to submit all of the assignments from the course. Ideally (in keeping with writing portfolio pedagogy), we would have allowed the students to select what they felt were their stron-

test pieces, but because we met only once weekly and the course was “low-stakes” (only a single credit), there weren’t enough assignments from which to choose. We nevertheless were able to design assignments about chemical engineering that would give the students an awareness of audience, introduce them to group writing, peer response, and revision, and give them practice writing reflective cover letters that would initiate a metacognitive approach to writing—that is, get them to think about the process of writing. Additionally, we stressed class discussion so that students would receive practice communicating ideas, responding to others’ ideas, and learning the language needed to participate in the discipline.

THE ACTIVITIES

The course had several activities that covered a variety of engineering topics integrated with communication issues. For the purposes of this paper, we summarize a few of the activities, then follow with a detailed discussion of two. Our emphasis in this paper is on portions of the course dealing with ethics/professionalism and understanding audience.

We started the course with a scavenger hunt that sent student teams to various faculty, the writing center, and some research facilities such as the electron microscope facility. Teams collected some technical information from each visit and gave an informal presentation on their findings.

A visual-rhetoric activity had students describe an assigned visual element that was related to chemical engineering (e.g., a pump) to a partner who had to draw it without looking at it. This activity gave students experience with precise verbal communication and active listening, while illustrating some basic chemical engineering principles. We then debriefed the class with their sometimes-humorous drawings, their guesses about what the devices were and what led them to their con-

cclusions, and then an explanation about the real function of the visual element.

To connect visual and verbal skills, students went to the Unit Operations lab for a demonstration of a pilot-scale distillation column. Prior to the lab visit, they were asked to develop and sketch a process for production of fuel-grade ethanol from a fermentation broth. This exercise introduced basic separation principles, including staging. The lab demonstration was combined with a quantitative problem assignment and a writing task that integrated all the elements. This was the first time any of the students had observed the operation of a larger-than-bench scale piece of chemical processing equipment.

The follow-up activity to the laboratory visit involved visits to actual industrial facilities. We wanted students to experience chemical engineering in the workplace and to have an opportunity to talk with practicing engineers in a more active way than a standard plant tour allowed. Each team visited a different site and spent several hours with a WPI alumnus during a major part of their workday. Companies visited included an environmental consultant’s site visit, membrane separations (Sepracor), and stem cell production (Viacell). After the trips, each group wrote a trip summary and gave a brief oral presentation to the rest of the class about the experience.

Although the activities described above provided some interesting exercises and opportunities for writing within a technical context, we really wanted to engage students at a deeper level. Course logistics and student background prevented going too far into the details of chemical engineering fundamentals, so we took a different route. Two activities, described below, resulted in some interesting issues and posed some particularly challenging problems for the instructors. Details about the course syllabus, assignments, and portfolios can be obtained directly from the authors at <dibiasio@wpi.edu> or <llebdusk@wheatonma.edu>.

*Ethics, Racism, and Engineering Practice*

Civic responsibility, the interaction of technology and society, and professional and ethical responsibility are all part of WPI’s educational philosophy, so in the first offering of the course we attempted to engage the class in issues of workplace racism. Wanting our students to realize that ethics and race issues have a place in chemical engineering and in their education as engineers, we used a campus event featuring a documentary about racism in Japan and a discussion with its director, and a real case-study involving a chemical company and allegations of racism. This exercise provided important data that only a collaboration would have provided.

The racial homogeneity of WPI, this class, and its instructors contributed to the impression that racism is something that occurs elsewhere and is perhaps not a real problem, and our all-too-brief treatment of the issue did little to counter
Our conclusion is that mixing writing and first-year engineering is certainly a stable solution when the experiment is properly conducted...Ensuring stability takes energy, time, and commitment from the faculty, however—it's a challenging and difficult process, but it is rewarding and fun.

that impression. Because the film examined racism in Japan, our students responded to the issue as if it were a symptom of Japanese culture in particular. Focusing on the lives of African-Americans in Japan and their isolation there, the film was interpreted by students as an instance of something that occurs outside the racial democracy of the United States. Our shift of the discussion to the Texaco racial-discrimination lawsuit[^13] did little to alter students’ perception that racism was something that occurred “out there.” Although we pointed out that the Texaco executives who had been accused of making racist remarks might have been trained in chemistry or engineering professions, our students nevertheless discussed the issue as if it were something that couldn’t happen here. When we shifted the discussion to subtle forms of racism that we have witnessed, such as unofficial segregation in the cafeteria or in fraternities, several students offered anecdotes about their best friends who were of color. We seemed to have created an atmosphere in which students felt the need to testify against racism and to represent themselves as among the enlightened, but our goal had been more to get students to consider the complexities of racism and to examine how they operate in the workplace. The exercise suffered from a larger cultural constraint in which “racism seems always to be an appendage to the classroom curriculum, something loosely attached to a course but not quite integral, even when race is the issue.”[^14]

We have not yet resolved the race issue to our satisfaction and will continue to explore ways to address it. We might consider, for example, having students explore how “whiteness” is often understood as a “non-race” or universal in the workplace. We might also consider examining race in the non-managerial levels of the workplace. At the same time, we consider the exercise successful because it provided us with information about our students’ perceptions that traditional lab activities cannot provide. Additionally, because the exercise was presented within the context of a chemical engineering class, it sent the message that racism is something that concerns chemical engineers.

Scheduling logistics and the issues described above caused us to reconsider our approach to introducing the grayer areas of professional decision-making. We assumed that a shift from the larger but harder-to-concretize issue of racism to other more clearly defined ethical dilemmas might be easier for students to grasp as an entry point into the profession’s complexities. So, in subsequent course offerings, we decided to focus on a very specific well-defined problem. Using an Online Ethics Center web site [http://www.onlineethics.org/], we designed an assignment to introduce students to common chemical engineering ethical dilemmas. We used a case study on “Request to Falsify Data” to generate in-class discussion about how the engineer in the case study might have responded if her manager wanted her to falsify data about an environmental oil spill. The writing assignment followed up on this discussion by asking students to evaluate the problem from the perspectives of a member of the state’s environmental protection agency, the CEO of the company, company attorneys, and members of the community.

Some students seemed surprised that engineering had an ethical component. As one student noted, “I never expected [a discussion about ethics] in a department other than Humanities. We discussed a dilemma between one’s future career and morality as part of the human community. From this discussion, I learned how ethical issues were involved with chemical engineering . . . I liked the idea that we had to give opinions from different perspectives.”

Another student found himself challenged by a situation that did not offer any moral certitude. By the end of the course, he described his dilemma: “It was hard to decide how other people would react and what they would do . . . Why would they want to jeopardize their career or the company and what qualities are needed to stand up for what is right?”

Because these exercises did not offer the students any answers, they introduced them to a significant but seldom-discussed component of chemical engineering as well as a language by which to begin considering the issues involved. The exercises provided practice in understanding and articulating multiple perspectives of the same scenario as well as the subjective context in which professional life across disciplines is situated.

Understanding Audience

A major group-writing piece involved describing a current field of chemical engineering research to a general audience. Student teams were assigned a research area and provided with at least one technical article describing that research, major benefits that might come from it, and problems associated with it. Each team did additional reading and produced an article written for the campus newspaper that described the role of chemical engineers in the specific research area. Some groups interviewed appropriate faculty with expertise in the area. The writing process allowed us to introduce techniques for collaborative writing, revision, and peer review.

The difficulties of understanding audience in an educational
context emerged as the students struggled to write to an audience of peers while recognizing that their professors would be reading and commenting on drafts. One group was assigned the research area of obesity drugs—a topic involving an interesting combination of medicine, biology, engineering, and patient treatment. In an effort to engage their prospective peer audience early in the piece and to be funny, the first draft of their paper appeared with the title in large, bold font: “What’s Up FATTY?” and a lead sentence of “Are you Fat? If so, read on.” Other examples of their humor included statements such as “The diseases related to obesity include heart disease, stroke, diabetes, hypertension, and gall BLADDER disease (ooooh!)....Scientists were exstatic [sic] when they discovered that the drug acts [sic] on the brain like COCAINE!!! Fortunately, it does not have the harmful side effects [sic] (you dope fiend)....Some people who are slightly overweight (not obese) are very emotionally disturbed because of society around them projecting the image that to be thin is better. They could then abuse the drug to become overly thin. Drugs for the MASSES. New drugs: Fad or PHAT.”

To a certain extent, the students’ article demonstrated a kind of “institutional under life,” which, in the writing classroom, is a productive assertion of identity against the one being taught. Robert Brooke, who adapted the sociological concept to explain student behavior in writing classes, notes that contrary to teacher responses that see such behavior as detrimental to instruction, such rebellion is actually productive because it indicates that students are acquiring a necessary critical distance from roles that are imposed on them. According to Brooke, such critical distance helps to form a more self-aware professional identity: “If the student in a chemistry class grew to think of herself as someone who thinks in certain ways to solve certain problems rather than as someone who must ‘learn’ equations to pass tests, then the student would begin to see herself as a chemist, and to act accordingly.”[5]

The review process included in-class peer revision and instructor comments. Both of those audiences suggested the writers consider the effect of their language on readers. The student team needed to recognize that their article’s message could be undermined by inappropriate humor. While some of the students’ peers might have been attracted to an article designed to entertain them, some of their peers would have been offended rather than entertained. Additionally, many newspaper readers seek information rather than amusement. We tried to point out that the campus newspaper ultimately serves the entire community and that student writing should reflect an understanding of that community. Their final version was titled “Obesity No More?” and led with “Have you ever wondered why someone can pig out and stay thin, while someone else can never seem to maintain a healthy weight? If so, read on.” The subsequent article replaced the earlier joking tone with one that was more formal: “If the drugs are approved, chemical engineers will be responsible for designing the necessary processes to produce the drug for the masses. Chemical engineers would also be working to produce the drugs more efficiently...Obese people could abuse the drug to become overly thin because of the influence of society. Society projects an overwhelming image that being thin is better.”

This group’s end-of-course portfolios indicated that they realized, in reflection, their initial drafts were offensive to some readers, but they also felt the revision process had taken the life out of the paper. Their cover letters pointed out that they were not interested in the topic from the beginning and had tried to find a way to make it interesting to each other: “Todd and I wanted to make it goofy enough for a college student, yet we all knew that some of our jokes would go over badly…. We managed to put together a pretty crude paper full of stupid remarks.” Rather than reflecting a lack of understanding of audience, these remarks suggest a kind of rebellion against it. Hence, their first draft was written suitably for their intended audience: their group. This draft also suited their purpose, which was to entertain and be entertained.

The subsequent revisions indicate a kind of capitulation to the educational system. As that same student noted in his portfolio letter, “The group got together again and took out all of the brazen humor to make what I thought was a dry article.” His comments reflect an understanding of the educational game in which the faculty audience is the final arbiter as well as his refusal or perhaps inability to identify with that audience. At this stage, he knows what his audience wants, and given that a grade is at stake, he will give that audience what it wants, but he will not identify with it. Also, he cannot fathom how someone would find the subject of obesity drugs relevant or interesting, but he is willing to play the language game.

This activity also made us question our experiences with the racism discussion. Again, those activities reflect the students’ desire to play the language game, which they interpreted as testifying against racism but did not reflect an understanding of what they themselves did not experience directly. These students could not imagine racism’s existence any more than they could imagine how someone would want to read an article about obesity that did not make jokes about it. Ultimately, both exercises attested to the need for education that requires students to imagine conditions and groups other than themselves as part of their intellectual maturation.

**EVALUATION**

We used several measures to assess student gains in knowledge of the chemical engineering profession and writing approach. To assess student gains in knowledge of the profession, an external evaluator administered questionnaires and conducted focus groups that categorized “knowledge” in three dimensions: “activities of chemical engineers, industries employing them, and issues faced by them.” To assess writing gains and to assess the reliability of our portfolio assessment, we used an external writing specialist. A final evalua-
tion measure involved student self-assessment as expressed in their portfolio cover letters.

After the first iteration of the course, the evaluator compared first-year chemical engineering majors who had taken the course to a control group of first-year chemical engineering students who had not. These pre- and post-comparisons were not useful due to the relatively small sample sizes. As a result, the evaluator turned to focus groups to provide a fuller understanding of what had happened.

We did not conduct any longitudinal studies, but it has been clear that students who took this course remained in the department. Many became active in the student AIChe society and others were academically outstanding. We believe this probably has more to do with the students' predisposition for chemical engineering as a major than the effects of a one-credit course.

**Gains in Knowledge of the Engineering Profession**

The evaluator concluded that the project had succeeded in producing gains in student knowledge of the activities in which chemical engineers engage. One of the greatest struggles for the students involved the group writing assignments, which they found difficult to complete because of incompatible schedules. Some also felt the course required too much writing for a single-credit course. In the second iteration of the course we addressed the group logistics problem by giving them more instruction in collaborative writing, fewer collaborative writing assignment, and more in-class time to write collaboratively. We did not decrease the frequency of writing assignments as we felt they were crucial to achieving our objectives.

**Gains in Approach to Writing**

To evaluate gains in student writing approaches, we designed a portfolio evaluation rubric that we provided to students at the beginning of the course. The rubric identified nine key criteria, each of which was ranked “Superior,” “Good,” “Acceptable,” or “Unacceptable.” A majority of “Superior” rankings earned the portfolio an “A”; a majority of “Good” earned a “B”; a majority of “Acceptable” earned a “C,” and a majority of “Unacceptable” earned an “NR” (“Not Recorded,” which is equivalent to a fail grade; WPI does not have a “D” or “F” grade). The portfolio review criteria were

- Demonstrates a robust understanding of the chemical engineering profession
- Shows sustained original, logical thinking
- Has strong organization at the paragraph and global level
- Demonstrates a strong sense of audience and voice; language is creative and appropriate; uses active voice wherever appropriate
- Uses grammar and mechanics to enhance meaning; has an interesting, credible voice
- Supports points thoroughly

• Takes risks that challenge the reader
• Is professionally presented
• Is complete and on time

DiBiasio and Lebduska then evaluated each portfolio independently. That is, we did not share our evaluations until we had ranked all of the portfolios. Although there was some disagreement over the ranking of specific criteria for certain portfolios, our overall rankings of the portfolios corresponded exactly, suggesting reliability. To further assess the reliability of our measures, the external writing specialist evaluated the portfolios using the same rubric and without knowledge of our evaluations. With the exception of one portfolio, her assessments correlated with ours, again suggesting a fair amount of portfolio assessment reliability. In the case of the exception, the evaluator assessed a grade of “NR,” while we had each assessed it as a “C.” In reviewing the materials, we concluded that our assessments had been influenced by our knowledge of the student, his participation in class, and the effort we assumed he had devoted to a low-credit, voluntary course.

The external evaluator of the portfolios concluded that “this course experience, as reflected in the student portfolios [was] valuable in contributing to student learning,”[12] but noted that although the students’ portfolio cover letters did reflect on their learning, they did not demonstrate an understanding of how the course’s various assignments were related. We attempted to address this deficiency by giving clearer letter-writing guidelines in the second iteration of the course.

Perhaps the greatest insights about the course came from the students themselves. Most of them recognized the marketability of the skills the course provided. The following quotes, which validate our interactionalist approach, are representative of what students wrote in their portfolio cover letters. One student, for example, wrote

Unless an engineer is involved in solitary research and development, he or she cannot expect to survive in the job market without superior communication skills. These skills are needed to get hired via an interview, to coherently and precisely express problems to the brass of the company, and to write technical reports that management can read without first acquiring an engineering degree.

Another wrote

On the field trip day I was very excited...The plant tour was unexpectedly amazing. It was nothing like those I saw in the movies. Another interesting fact was that the whole building was designed to be explosion proof, even inside the elevator...Chemical Engineering and Communications class was a very unique opportunity offered to me. It was nothing like other classes in WPI where I took notes on the lectures and discussed them in groups, I felt that I learned something new every class meeting. It was like a combination of different subjects that would help prepare a future Chemical Engineer for the real world out there.

And finally

What did I learn from this course? Well, I was exposed to environmental conservation organizations and I saw equipment used at the industrial level being implemented to be environmentally friendly....
SENSITIVITY ANALYSIS IN ChE EDUCATION*

Part 2. Application to Implicit Models

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In Part 1 of this series,[1,1] we emphasized the importance of sensitivity analysis (SA) in chemical engineering pedagogy and described its application to the class of engineering models expressible in explicit form, \( y = f(x; p) \). Here, in Part 2, we consider applications of SA to the more complex class of models expressed in the implicit form,

\[
f(y, x; p) = 0
\]

where \( y \) is the vector of \( N \) outputs, \( x \) is the vector of \( J \) system variables, and \( p \) is the vector of \( K \) constitutive parameters. Implicit models can take many forms; their distinguishing property is that Eq. (1) cannot be “solved analytically” for \( y \) in terms of the inputs (although we typically assume that the solution of the equations is unique).

In Part 1, we showed how to use SA to determine and employ the sensitivity coefficients of the output quantities with respect to \( x \) and to \( p \). In this paper, we similarly discuss SA in relation to several types of implicit models, including sets of nonlinear equations, systems of ordinary differential equations, and unconstrained optimization problems (including regression analysis). For an explicit model, determining the sensitivity coefficients is relatively straightforward; for an implicit model, this is usually a more complex task.

We then demonstrate the use of SA for a particular implicit model arising in thermodynamics concerning two-phase equilibrium of a pure substance, for which the underlying model is a set of nonlinear equations with one system variable and several constitutive parameters. Since calculation of the sensitivity coefficients for an implicit model is a more complex task, we focus here on their calculation and use for the system variable and for the constitutive parameters. We use the former to illustrate the use of SA as a unifying theme, in this case involving thermodynamics; we use the latter to address items 1a and 1b of Part 1.[1,2] Thus,

1. We show the application of SA to the set of nonlinear equations for vapor-liquid equilibrium (pure substance) arising from equating the chemical potentials and pressures of the coexisting phases. The resulting implicit model determines the coexistence properties (output quantities) \( \{p^v, v^v, v^l \} \) in conjunction with an EOS involving the three constitutive parameters: critical temperature, \( T_c \), critical pressure, \( P_c \), and acentric factor, \( \omega \). Here, \( p^v \) is the vapor pressure, and \( v^v \) and \( v^l \) are the molar volumes of the vapor and liquid phases, respectively. From this model, we calculate the first- and second-order sensitivity coefficients of the output quantities with respect to the single system variable, \( T \).

2. We show how SA can be used to calculate the uncertainties of the outputs \( \{p^v, v^v, v^l \} \) in terms of the uncertainties of the constitutive parameters \( \{T_c, P_c, \omega \} \).

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of an underlying three-parameter EOS employed in the nonlinear equation model for pure-fluid vapor-liquid equilibrium.

OVERVIEW OF IMPLEMENTATION OF SA FOR IMPLICIT MODELS

As discussed in Part 1, the implementation of SA requires calculation of sensitivity coefficients. For an explicit model, their calculation is relatively straightforward; for an implicit model, their calculation depends on the particular type of model. We briefly sketch how sensitivity coefficients are calculated for several implicit models arising in chemical engineering: sets of nonlinear equations, systems of ordinary differential equations, and unconstrained optimization. The resulting expressions are scattered in the literature, and it is useful to present them all here.

For an implicit model defined by a set of nonlinear algebraic or transcendental equations

\[ f_i(y, x; p) = 0 \quad i = 1, 2, ..., N \]  

(2)

the first-order sensitivity coefficients of \( y \) with respect to \( x \) or \( p \) are obtained by partial differentiation using the chain rule. Thus, for the system variables \( x \) or \( p \)

\[ \sum_{k=1}^{N} \left( \frac{\partial f_i}{\partial y_k} \right) \left( \frac{\partial y_k}{\partial x_j} \right)^* = \left( \frac{\partial f_i}{\partial x_j} \right)^* \quad i = 1, 2, ..., N; \quad j = 1, 2, ..., J \]  

(3)

where \( * \) denotes evaluation at the solution to Eqs. (2). Equations (3) are a set of \( NJ \) linear algebraic equations in the sensitivity coefficients \( \frac{\partial y_i}{\partial x_j} \). The result for the sensitivity coefficients \( \frac{\partial y_i}{\partial p_j} \) is analogous to Eqs. (3). We illustrate below the use of Eqs. (3) by means of a numerical example.

An implicit model defined by a system of first-order ordinary differential equations (ODEs) is expressed as

\[ \frac{dy_i}{dt} = g_i(y, t; x, p) \quad i = 1, 2, ..., N \]  

(4)

\[ y_i(0) = y_{0i} \quad i = 1, 2, ..., N \]  

(5)

The first-order sensitivity coefficients of Eq. (4) with respect to the constitutive parameters \( p \) are obtained by differentiation of Eq. (4) to give

\[ \frac{d}{dt} \left( \frac{\partial y_i}{\partial p_j} \right) = \frac{\partial g_i}{\partial p_j} + \sum_{k=1}^{N} \left( \frac{\partial g_i}{\partial y_k} \right) \left( \frac{\partial y_k}{\partial p_j} \right) \quad i = 1, 2, ..., N; \quad j = 1, 2, ..., K \]  

(6)

\[ \left( \frac{\partial y_i}{\partial p_j} \right)(0) = 0 \]  

(7)

The corresponding equations for \( \frac{\partial y_i}{\partial x_j} \) are obtained by replacing \( p_j \) with \( x_j \).

We can also consider the initial conditions of Eq. (5) as additional constitutive parameters; the sensitivity coefficients with respect to these are given by the analogs of Eqs. (6) and (7).

For an implicit model defined by an unconstrained optimization problem

\[ \min_y f(y; p) \]  

(10)

the outputs are the values at the optimal solution, \( y^* \). The first-order necessary conditions for optimization are

\[ \frac{\partial f}{\partial y_i}(y; p) = 0 \quad i = 1, 2, ..., N \]  

(11)

To calculate the sensitivity coefficients of the optimal solution to changes in the constitutive parameters \( p \), we can treat Eqs. (11) as a set of nonlinear equations and apply Eqs. (3) to give

\[ \sum_{j=1}^{N} \left( \frac{\partial^2 f}{\partial y_j \partial y_j} \right) \left( \frac{\partial y^*}{\partial p_k} \right)^* = \left( \frac{\partial^2 f}{\partial y_j \partial p_k} \right)^* \quad i = 1, 2, ..., N; \quad k = 1, 2, ..., K \]  

(12)

Equations (12) are a set of linear algebraic equations for \( \frac{\partial y^*}{\partial p_k} \) involving the second-order coefficients of \( f \) at the optimum, \( \left( \frac{\partial^2 f}{\partial y_j \partial y_j} \right)^* \) and \( \left( \frac{\partial^2 f}{\partial y_j \partial p_k} \right)^* \).
We can also consider changes involving functions of the output variables \( y \) in an implicit model. For example, a typical parameter-estimation problem involving an engineering model can be viewed as an implicit model in which the parameters are outputs \( y \) obtained by minimizing the sum of squares of deviations of a model from a set of observed data. The values of the objective function at parameter values near the optimal solution are important in determining their joint confidence regions\(^{13}\) (their uncertainties in a statistical sense). Thus, the change in the residual-sum-of-squares objective function, \( \Delta f \), from the optimal value is given approximately by the Taylor expansion

\[
\Delta f = \sum_{i=1}^{N} \left( \frac{\partial f}{\partial y_i} \right) \delta y_i + \sum_{i=1}^{N} \sum_{j=1}^{N} \frac{\partial^2 f}{\partial y_i \partial y_j} \delta y_i \delta y_j
\]

where the first-order term vanishes because of Eqs. (11). Equation (13), involving the second-order sensitivity coefficients, defines an ellipsoidal confidence region for the parameters for a specified value of \( \Delta f \). This region, defined by the set of all parameter values such that the right side of Eq. (13) is less than or equal to the left side, can be viewed as the parameter region that yields an acceptable uncertainty in the residual sum of squares.

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SENSITIVITY COEFFICIENTS FOR COEXISTENCE PROPERTIES OF VAPOR-LIQUID EQUILIBRIUM

For a pure fluid, \( \{p^e, v^g, v^f\} \) are output quantities arising from a model consisting of a set of three nonlinear equations involving an EOS that is assumed to be applicable to both liquid and gas/vapor phases. The model equations result from equating the chemical potentials and the pressures of the coexisting phases (at a given \( T \)). The former equality gives rise to Maxwell's equal-area rule\(^{14}\) (first enunciated independently by Maxwell\(^{15}\) and by Clausius\(^{16}\)).

\[
\oint_{v^g} \left( \frac{dp}{dT} \right) dv
\]

Differentiation of Eq. (15) (involving differentiation of the integral) gives

\[
\frac{dp^e}{dT} = \int_{v^g}^{v^f} \left( \frac{dp}{dT} \right) dv
\]

Differentiation of Eqs. (15) and (16) (involving application of the chain rule) gives

\[
\frac{dp^e}{dT} = \left( \frac{\partial P}{\partial v} \right)_v + \left( \frac{\partial P}{\partial v} \right)_p \frac{dv^g}{dT}
\]

In these equations, with respect to the derivatives on the right side, \( \sigma \) denotes "along the saturation curve," and superscripts \( g \) and \( f \) refer to evaluation at \( (v^g, T) \) and \( (v^f, T) \), respectively; all quantities are evaluated at the saturation conditions corresponding to \( \{p^e, v^g, v^f, T\} \).

The sensitivity coefficients are available analytically from Eqs. (17) to (19) as

\[
\frac{dp^e}{dT} = \int_{v^g}^{v^f} \left( \frac{dp}{dT} \right) dv
\]

The numerical solution of Eqs. (14) to (16) is part of the calculations described in the following example.

We now turn our attention to the sensitivity coefficients for this implicit model. Equations (14) to (16) are three equations in the three outputs \( \{p^e, v^g, v^f\} \), with the system variable \( T \), for a given set of constitutive parameters, \( p \) (which we consider to be fixed in this section, and for simplicity suppress their appearance in the following equations). We carry out a first-order sensitivity analysis of the model by differentiating the equations with respect to \( T \), to give a set of three linear equations for the sensitivity coefficients

\[
\left( \frac{dp^e}{dT} \right)_T, \quad \left( \frac{dv^g}{dT} \right)_T \quad \text{and} \quad \left( \frac{dv^f}{dT} \right)_T
\]

in the form of Eqs. (3). The notation signifies evaluation at the solution of Eqs. (14) to (16). These are ordinary (as opposed to partial) derivatives, since there is a single system variable, \( T \).

Differentiation of Eq. (14) (involving differentiation of the integral) gives

\[
\frac{dp^e}{dT} = \int_{v^g}^{v^f} \left( \frac{dp}{dT} \right) dv
\]

Differentiation of Eqs. (15) and (16) (involving application of the chain rule) gives

\[
\frac{dp^e}{dT} = \left( \frac{\partial P}{\partial v} \right)_v + \left( \frac{\partial P}{\partial v} \right)_p \frac{dv^g}{dT}
\]

where \( P(v, T; p) \) represents the EOS, and we explicitly denote the dependence of the outputs on the system variable \( T \) and the constitutive parameters of the EOS, \( p \). (Equation 14 was given, in effect, by Planck.)\(^{17}\) The pressure equality results in two additional equations involving the EOS

\[
\frac{dp^e}{dT} = \int_{v^g}^{v^f} \left( \frac{dp}{dT} \right) dv
\]
where the cyclic derivative rule has been used to obtain the final terms in each of Eqs. (21) and (22). (Equations of the type of 21 and 22 were obtained by Planck.\cite{planck})

Equations (20) through (22) can be differentiated again to obtain the second-order sensitivity coefficients on the saturation curve, which are given by

$$
\frac{d^2 p^\sigma}{dT^2} = \frac{1}{\nu - \nu'} \left[ \frac{\partial p}{\partial T} \left( \frac{dv}{dT} \right)_\sigma - \frac{\partial p}{\partial v} \left( \frac{dv}{dT} \right)_\sigma \right] - \frac{dp}{dT} \left[ \left( \frac{dv}{dT} \right)_\sigma - \left( \frac{dv'}{dT} \right)_\sigma \right] + \int_{\nu'}^{\nu} \left( \frac{d^2 p}{dT^2} \right)(v,T)dv
$$

The derivatives \( \partial p/\partial p \) on the right side are evaluated from the EOS holding fixed \( v \) and \( T \), and all parameters other than \( p \). The derivatives \( \partial p/\partial v \), \( \partial p/\partial T \), are evaluated at fixed values of all constitutive parameters, as in Eqs. (20) through (22).

If we denote the relative uncertainties in the three constitutive parameters by \( u(ln p) \), the relative uncertainties in the three output quantities, \( u(ln y) \), are given by the analog of Eq. (9) of Part 1\cite{part1}

$$
2 u^2(ln y_i) = \sum_{i=1}^{3} \left( \frac{\partial ln y_i}{\partial ln p_j} \right)^2 u^2(ln p_j)
$$

where we assume that the input uncertainties are uncorrelated. The upper and lower (95\%) uncertainty limits for \( y_i \) are then calculated from

$$
y_i(\text{upper}) = y_i \exp\left[ 2u(ln y_i) \right] \quad y_i(\text{lower}) = y_i \exp\left[ -2u(ln y_i) \right]
$$

**NUMERICAL EXAMPLE**

As a numerical example of items 1a and 1c of Part 1\cite{part1} or 1 and 2 above, we consider the calculation of \( \{p',v',v''\} \) for toluene, their sensitivity coefficients with respect to \( \{T_e, P_e, \omega\} \) as functions of \( T \) from the triple-point temperature, \( T_e \), to \( T \), and the use of the latter in uncertainty analysis in conjunction with the Peng-Robinson EOS\cite{peng}

$$
P = \frac{RT}{v-b} - \frac{a(T)}{v(v+b)+b(v-b)}
$$

where

$$
a(T) = 0.45724 \frac{R^2 T_e^2}{P_e} \alpha(T)
$$
The derivatives required in Eqs. (26) through (28) are given from Eqs. (31) through (35) by

\[
\frac{\partial P}{\partial T} = -\frac{\partial b}{\partial T} \frac{RT}{P_c} + \left( \frac{\partial b}{\partial T} + \frac{2\alpha(T)(v-b)}{v(v+b)+b(v-b)} \right) - \frac{a(T)}{v(v+b)+b(v-b)} \frac{\partial \ln a(T)}{\partial \ln p_j} \quad (36)
\]

\[
\frac{\partial \ln a(T)}{\partial \ln T_c} = 2 + \frac{\partial \ln \alpha(T)}{\partial \ln T_c} = 2 + \alpha(T) \left( \frac{T}{T_c} \right)^{0.5} \kappa(\omega) \left( \frac{T}{T_c} \right) \quad (37)
\]

\[
\frac{\partial \ln a(T)}{\partial \ln P_c} = -1 \quad (38)
\]

\[
\frac{\partial \ln a(T)}{\partial \ln P} = \frac{\partial \ln \alpha(T)}{\partial \ln P} = \left[ 1 - \left( \frac{T}{T_c} \right)^{0.5} \right] \left[ \frac{\partial \ln \kappa(\omega)}{\partial \ln \omega} \right] = 2\omega \left[ \alpha(T) \right]^{0.5} \left[ 1 - \left( \frac{T}{T_c} \right)^{0.5} \right] \quad (39)
\]

\[
\frac{\partial b}{\partial \ln T_c} = 1 \quad (40)
\]

\[
\frac{\partial b}{\partial \ln P_c} = -1 \quad (41)
\]

\[
\frac{\partial b}{\partial \ln P} = 0 \quad (42)
\]

\[
\left( \frac{\partial P}{\partial T} \right)_T = -\frac{\partial b}{\partial T} \frac{RT}{P_c} + \frac{2\alpha(T)(v-b)}{v(v+b)+b(v-b)} \quad (43)
\]

We have used Maple\(^{(9)}\) to calculate the coexistence properties \((p^*, v^*, v^f)\) from Eqs. (14) through (16) and their sensitivity coefficients from Eqs. (26) through (28), with \(p_j = T_c P_c, \omega\) in turn. A Maple script is available on the web site at <http://www.chemical-stoichiometry.net/sensitivity/>.

Figure 1 shows the normalized sensitivity coefficients with respect to the constitutive parameters \((P_c, T_c, \omega)\) as functions of \(T\), from the triple-point temperature, \(T_\text{t}c\), to \(T_c\), using the nominal parameter values for toluene \((10)\) (42.365 kPa, 593.95 K, 0.26141) \((\omega = \text{calculated from the vapor pressure equation given by Goodwin}^{(9)})\). The ordinate values can

Figure 1. Normalized sensitivity coefficients with respect to \((P_c, T_c, \omega)\) for toluene from PR EOS over entire liquid range \((T_\text{t}c = 293.15 \text{ K to } T_c = 593.95 \text{ K})\): \((a)\) for \(p^*\); \((b)\) for \(v^*\); \((c)\) for \(v^f\).
be interpreted as the % change in the output for a 1% change in the input.\(^1\)

The most important parameter for all three output variables is \(T_c\). For \(p^o\) (Figure 1a), the sensitivity coefficient with respect to \(T_c\) is negative, and increases in magnitude from about 7% near \(T_c\) to over 28.5% at the triple point (\(T_r = 178.15\) K\(^{10}\)). The corresponding coefficients of \(v^e\) (Figure 1b) and \(v^f\) (Figure 1c) both become infinite in magnitude at \(T_c\). At lower temperatures, the coefficient of \(v^e\) is much larger in magnitude than that of \(v^f\). The latter coefficient decreases from 0.9 at \(T_1\) to become negative at \(T = 461\) K, and increases rapidly in magnitude as \(T\) approaches \(T_c\). The former coefficient is always positive, starting at 28.5 at \(T_r\), going through a minimum at \(T = 486\) K, and rapidly increasing in magnitude as \(T\) approaches \(T_c\). Voulgaris, et al.,\(^{11}\) have also reported on the “extreme sensitivity of \(p^o\) to \(T_c\)” for various fluids, although they did not use SA in their investigation.

The sensitivity coefficients with respect to \(P_c\) are much smaller in magnitude than those with respect to \(T_c\), and all have constant numerical values (+1 for \(p^o\) and −1 for \(v^e\) and \(v^f\)), results not anticipated prior to the numerical calculations. In retrospect, however, it was realized that this follows from the fact that the Peng-Robinson EOS is, in effect, a two-parameter EOS with the acentric factor \(\omega\) incorporated into the parameter \(a\), via a function of the reduced temperature, \(T_r = T/T_c\). For all such EOS, including a strictly two-parameter EOS such as the van der Waals, the reduced vapor pressure, \(p^o/P_c\), is a universal function \(\phi_1\) of \(T_r\) and \(\omega\)

\[
p^o = P_c\phi_1(T_r, \omega) \quad (44)
\]

Differentiation of Eq. (44) then gives

\[
\frac{\partial \ln p^o}{\partial \ln P_c} = 1 \quad (45)
\]

as in Figure 1a.

Similarly, as in Eq. (44), the liquid and vapor saturation volumes are also universal functions of \(T_r\) and \(\omega\)

\[
v^e = v_c\phi_2(T_r, \omega); \quad v^f = v_c\phi_3(T_r, \omega) \quad (46)
\]

Also, the Peng-Robinson or similar EOS each has a universal value of the compressibility factor at the critical point

\[
z_c = \frac{P_c v_c}{RT_c} \quad (47)
\]

Taking logarithms and differentiating both members of Eq. (46) and Eq. (47) with respect to \(\ln P_c\), we obtain

\[
\frac{\partial \ln v^e}{\partial \ln P_c} = -1 \quad (48)
\]

as in Figures 1b and 1c.

The sensitivity coefficients with respect to \(\omega\) are also much smaller in magnitude than those with respect to \(T_c\), with that of \(p^o\) being the largest. This coefficient (Figure 1a) is negative and increases from −5.2% at \(T_1\) to zero at \(T_c\). The coefficient of \(v^e\) with respect to \(\omega\) (Figure 1b) is positive and decreases from 5.2% at \(T_1\) to zero at \(T_c\); for \(v^f\), it is negative and very small (of magnitude less than 0.06%).

Figure 2 shows the output quantities \(p^o\) (Figure 2a), and \(v^e\) and \(v^f\) (Figure 2b) in the form of the T-v binodal curve, together with uncertainty bands calculated from Eqs. (29) and (30), assuming 2.5% uncertainties in each of the constitutive parameters, \(\{P_c, T_c, \omega\}\), i.e., with \(2\sigma(\ln p^o) = 0.05\). The experimental points in Figure 2a, for comparison with the calcu-
lated PR EOS results (nominal values), are given by Goodwin.\textsuperscript{[10]} The relatively large uncertainty of 2.5% in the parameters was chosen to illustrate relatively large uncertainty bands for the outputs. For a species such as toluene, 2.5% is a much greater uncertainty than arises from experimental measurements.\textsuperscript{[12]} If the critical constants must be estimated, however, the uncertainties may be of comparable or greater magnitude.\textsuperscript{[11,13]}

In Figure 2a, the uncertainty bands for $p^o$ arise primarily from the uncertainty in $T_c$, as indicated by Figure 1a. The spread of the uncertainty bands increases as $T 	o T_c$. This is because, although the relative sensitivity coefficient decreases as $T$ increases (Figure 1a), the value of $p^o$ increases more rapidly. At low temperatures (below about 350 K), the relatively large sensitivity coefficient applies to very small values of $p^o$, and the resulting spread is imperceptible on Figure 2a. For CO$_2$, a substance with a much larger vapor pressure at $T_c$, the uncertainty bands are more prominent, even for 0.5% uncertainty (not shown here).

In Figure 2b (in which the abscissa is a logarithmic scale), below $T_c$ (up to about 550 K), there is a considerable uncertainty spread in the $v^o$ values, but this is barely perceptible in the $v^f$ values. The reasons for this correspond to those for the corresponding spreads in the $p^o$ values. As $T_c$ is approached, the uncertainty bands approach infinite magnitude, because of the similar behavior of the sensitivity coefficients of $v^o$ and $v^f$ with respect to $T_c$; these coefficients completely dominate the determination of the uncertainty bands. In this region, the first-order SA expansion corresponding to Eq. (30) gives these as

$$v^o = v^o(593.95) \exp \left[ \pm 2u(T_c) \frac{\partial \ln v^o}{\partial \ln T_c} \right]$$
$$v^f = v^f(593.95) \exp \left[ \pm 2u(T_c) \frac{\partial \ln v^f}{\partial \ln T_c} \right]$$

(49a, b)

The inset shows the breakdown of this expansion near the critical point, using an even smaller uncertainty in $T_c$ of 0.5% ($2u(T_c) = 0.01$). The solid curves are the actual binodal curves calculated using parameter values for $T_c$ of 1% above and below the nominal value of $T_c = 593.95$ K. The dashed and dotted curves are the results for $v^o$ and $v^f$, respectively, from Eq. (49a,b); a few degrees below (the nominal) $T_c$, they agree with the solid curves, but near $T_c$ they become increasingly inaccurate.

This example shows that one must beware when sensitivity coefficients become infinite in magnitude. The first-order SA expansion cannot be applied to situations when the output variable is not analytic for some values of the input quantities, i.e., does not have a Taylor series expansion. The phenomenon we have discovered numerically here is related to the non-analyticity of the quantity $(v_{sat} - v)_{sol}$ as a function of $(T-T_c)$.\textsuperscript{[14]}

**CONCLUSIONS (Parts 1 and 2)**

1. Sensitivity analysis (SA) is an important pedagogical topic that should be explicitly included in the chemical engineering curriculum in many courses.

2. SA can serve as a unifying theme for various topics involving engineering models, since, among other things, it can show the relative importance of changes in input quantities as they affect output quantities ("the solution").

3. SA is applicable to both explicit engineering models (Part 1) and implicit ones (Part 2), whether they involve algebraic, transcendental, or differential equations, or optimization problems.

4. The elementary aspects involving sensitivity coefficients can be introduced into the undergraduate curriculum, since they only require a background in multivariable calculus. This includes an introduction to uncertainty analysis.

5. Additional aspects of SA may have to be deferred to the graduate curriculum. These include overall effects of changes in system variables on the solution, which needs a background in linear algebra, which, in turn, may not be required of all undergraduates.

**ACKNOWLEDGMENTS**

Financial assistance has been received from the Natural Sciences and Engineering Research Council of Canada. C. Stuart assisted with the graphics.

**REFERENCES**

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9. MAPLE is a registered trademark of Waterloo Maple, Inc.
Mixing Writing with First-Year Engineering
Continued from page 253.

was subjected to morally stimulating situations which made me think, which is novel and frightening. And finally I was presented with two projects that would be assigned to everyday chemical engineers. In my opinion I feel that I have learned something about the chem. eng. profession and that I must remember to communicate my ideas to others succinctly and clearly as I take the roller coaster ride of education towards the tunnel of real life working environments.

CONCLUSIONS

For both students and faculty, this course experiment seemed to move in a promising direction. On a professional development level, the activity lessened the widening "gulf of mutual incomprehension" between scientists and humanists that C.P. Snow said threatened the quality of intellectual life.[16] DiBiasio and Lebduska each gained insight into how the other half lived, into the priorities informing engineering and humanities education, and on how the two sides, too often thought of dichotomously, might speak to each other in the classroom. Equally important was the opportunity to allow students to hear the conversation—that is, to experience chemical engineering as a practice that is informed by humanities values, including clear and ethical communication.

Our conclusion is that mixing writing and first-year engineering is certainly a stable solution when the experiment is properly conducted. In our opinion, the unstable solution, represented by segregated technical writing courses and engineering writing that emphasizes only lab reports, is not as productive. Ensuring stability takes energy, time, and commitment from the faculty, however—it’s a challenging and difficult process, but it is rewarding and fun. The students will also be challenged, not just by trying to understand a profession they think they want to pursue, but also by being engaged in thinking through writing. Generally, that’s a new concept for most of them.

For the most part, the activities we designed accomplished our original goals while providing us with greater insight into first-year students. In her evaluation of the portfolios, the external writing specialist noted

Such opportunities for students to reflect on their learning—what they learned, what it means, why it is important, etc.—are critical components of effective portfolios, and they distinguish portfolios from other kinds of student learned assessment (tests, essays, and so on).[21]

The course experience, in other words, not only provided students with information about chemical engineering, but it offered them an opportunity to gain knowledge about it—that is, a means by which they could reflect about the information and place it within the context of their overall lives.

Despite problems such as course logistics, students’ time constraints, and a kind of cultural resistance to writing, most students demonstrated growth in their knowledge of the profession and their use of communication as a learning tool. Additionally, we discovered that a collaboration between seemingly unrelated disciplines aids in faculty development (an opportunity to see how the other half thinks), but to be truly effective this approach needs to be transported beyond the two involved faculty members to a more globalized WAC endeavor.

Recently, the chemical engineering department voted to expand the course and now offers a full 3-credit introduction to chemical engineering on a two-year trial basis. The course counts toward graduation requirements and it is expected to become a permanent part of the department’s curriculum.

REFERENCES

A BATCH FERMENTATION EXPERIMENT FOR L-LYSINE PRODUCTION

In the Senior Laboratory

DAVID R. SHONNARD, EDWARD R. FISHER, DAVID W. CASPARY
Michigan Technological University • Houghton, MI 49931-1295

Biochemical processes are finding increasing application in the chemical industry for the production of a wide variety of products from renewable resources. These products include pharmaceuticals, consumer and food products, fuel additives, industrial enzymes, and many others. They are typically created using batch processing, a marked departure from the more traditional continuous processes for commodity chemicals. Recent graduates from chemical engineering programs are finding more opportunities for employment in industries that use biochemical processes and perhaps fewer opportunities on a percentage basis in traditional commodity chemical and petrochemical production. In this experiment, student groups produce L-lysine, an essential amino acid, from a glucose minimal defined media in batch culture (fermentation). In this article, we will describe the pedagogical approach, the objectives for a semester-long design of experiments, and key results from the fermentation experiment.

Biochemical processes are complex, involving multiple steps in converting raw material into products. In addition, preparation steps and downstream separations are not typical of traditional chemical processing. Examples of chemical engineering laboratory experiments using biochemical processes have recently appeared. In these experiments, ethanol is typically produced in short-duration experiments that are, by necessity, abbreviated and less complex than most industrial fermentations. In order to prepare undergraduates for opportunities in biochemical processing and to provide a laboratory experience with a complexity similar to a commercial process, we have developed a batch fermentation experiment to produce L-lysine for the senior laboratory.

Figure 1. Batch fermentation experiment for L-lysine product from a defined minimal media containing glucose

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OVERVIEW OF THE EXPERIMENT

The L-lysine batch fermentation experiment is shown schematically in Figure 1. It is conducted using a 5-liter bioreactor (New Brunswick Scientific BioFlow3000) and a data acquisition and control system (New Brunswick Scientific BioCommand). With this system, students study the kinetics of microbial growth and L-lysine production under controlled conditions of temperature, pH, dissolved oxygen (DO), and agitation. Auxiliary equipment includes a mobile autoclave sterilizer (New Brunswick Scientific) and a media microfiltration unit (Fisher Scientific).

Approximately 60 to 100 senior-year chemical engineering students annually conduct the batch fermentation experiment in the “Chemical Plant Operations Laboratory” course. Due to the complexity of this experiment, students work in teams comprised of two 4-member groups. The fermentation experiment requires two to three days of continuous operation to complete due to the slow kinetics of cell growth and L-lysine production. Table 1 shows the sequence of events for this experiment.

PEDAGOGICAL OBJECTIVES

The first pedagogical objective for the fermentation experiment is to introduce the students to biochemical process equipment and to explain the key steps for production of a biochemical product. Because most of the graduating seniors have little or no biochemistry or biochemical engineering experience, the experiment objectives are geared toward an introductory treatment. Prior to conducting the experiments, we give a 2-hour orientation and provide background information on L-lysine production using Corynebacterium glutamicum (American Type Culture Collection, ATCC No. 21253), we conduct a tour of the laboratory, and hold a discussion of experiment objectives.

We give background information in an oral presentation to the 8-member student team and describe cell growth in the context of the major growth stages: lag, exponential, deceleration, stationary, and death. Specific metabolic characteristics of C. glutamicum are described as shown in Figure 2.[5] We further explain that due to a mutation in the cellular DNA by chemical treatment, this cell cannot convert aspartyl semialdehyde to L-homoserine. In order to grow the cells on a glucose minimal medium, L-methionine, L-isoleucine, and L-threonine must be added in trace amounts. Once these supplemented amino acids are consumed by growth, any remaining glucose is converted to L-lysine rather than cell mass. We explain that concerted feedback inhibition of the enzymatic conversion of L-aspartic acid to aspartyl phosphate is relaxed as L-threonine is consumed, thus allowing overproduction of L-lysine. When these concepts are understood, we tell the students that cell growth and product formation are expected to occur separately in the batch culture. One of the objectives for the student teams is to test this hypothesis and also to determine if the amount of supplemented amino acids controls the maximum concentration of cells in the fermentation.

The second part of the orientation is a tour of the laboratory facilities. We describe each piece of equipment and explain its purpose in the production of L-lysine. We emphasize the importance of maintaining sterile conditions and show the students the two methods of sterilization used; steam autoclaving for the bioreactor and microfiltration for the growth media. We discuss scale-up and the need for coordinating processes at smaller scales to support production at a larger scale (e.g., flask-scale cultures for inoculating the fermenter and the associated equipment). Finally, we explain that the safety aspects of the laboratory are consistent with Biosafety Level I requirements (Center for Disease Control, CDC). The

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**TABLE 1**

<table>
<thead>
<tr>
<th>Schedule for L-lysine Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
</tr>
<tr>
<td>Proposal preparation</td>
</tr>
<tr>
<td>Pre-laboratory check-in</td>
</tr>
<tr>
<td>Laboratory experiment</td>
</tr>
<tr>
<td>Post-laboratory oral presentation</td>
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<tr>
<td>Final report preparation</td>
</tr>
</tbody>
</table>

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**TABLE 2**

<table>
<thead>
<tr>
<th>Experiment Plan for Cell Growth and L-lysine Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Amino acid base case values are L-threonine (150 mg/L), L-methionine (40 mg/L), and L-leucine (100 mg/L))</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Amino Acid Concentration</th>
<th>Glucose Concentration (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>1. Low (50% lower)</td>
<td>Team 2</td>
</tr>
<tr>
<td>2. Base case</td>
<td>Team 1</td>
</tr>
<tr>
<td>3. High (50% higher)</td>
<td>Team 3</td>
</tr>
</tbody>
</table>

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*Figure 2. Feedback inhibition for regulation of L-lysine synthesis within the cell. Dashed lines indicate feedback inhibition of key enzymes in the metabolic pathway (solid lines).*
last part of the orientation is a discussion of handout materials (available upon request by e-mail from <drshonna@mtu.edu>) and a schedule for meeting the requirements as outlined in Table 1.

Another pedagogical objective is to test the effects of initial glucose and amino acid concentrations on L-lysine production and cell growth in a design of experiments. As shown in Table 2, this design of experiments involves six teams during the semester. The goal is to involve the student teams in a continuous improvement exercise and to increase their understanding of how fermentation parameters affect cellular growth and L-lysine production. Each team conducts an experiment at different initial glucose and amino acid concentrations. During the semester, as experiments are completed and results become available, sharing the data with the other student teams is intended to increase the level of understanding about this fermentation process for the entire class. Student teams share their results by attaching reports and presentations to an e-mail to the instructor—the cumulative results (as shown later in Table 6) are then organized and disseminated by the instructor to the student teams (by e-mail attachment) during the final days of the semester.

**EXPERIMENTAL METHODS**

Following the orientation, each team prepares and submits a proposal in which students demonstrate their familiarity with the process equipment, the objectives, laboratory safety (chemical, physical, and biological hazards), sample calculations, and the market aspects of their product. Because of scheduling limitations, during the 52-hour experiment the teams are split into two groups. One group from the team initiates the fermentation over a 4-hour period. This involves formulating the growth medium, assembling and autoclaving the bioreactor, sterilizing the medium and transferring it to the bioreactor using microfiltration, calibrating O₂ and pH probes, and finally inoculating with flask-grown cells. During the next 48 hours, all students in the team periodically sample for cell growth, glucose consumption, and L-lysine production (no sampling is done between midnight and 8 a.m., however).

Each run in the experiment plan is conducted under identical conditions of temperature (30°C), pH (7.0), dissolved oxygen (50% of saturation with air), and duration (52 hours). The experiment objectives given to each team are shown in Table 3. The maximum specific growth rate is obtained by applying the Monod equation [6] to the definition of the specific growth rate, \( \mu \), as

\[
\mu = \frac{1}{X} \frac{dX}{dt}
\]  

(1)

where \( X \) is the concentration of cells in the medium (g/L). The Monod equation is

\[
\mu = \mu_{\text{max}} \frac{S}{K_S + S} \frac{A}{K_A + A}
\]

(2)

where \( \mu_{\text{max}} \) is the maximum specific growth rate constant (hr⁻¹), \( S \) and \( A \) are the concentration of glucose and supplemented amino acids, respectively (g/L), and \( K_S \) and \( K_A \) are the half saturation constants (g/L). At the start of the fermentation, \( S >> K_S, A >> K_A \), and therefore \( \mu = \mu_{\text{max}} \) in Eq. (1). The solution to Eq. (1) for exponential growth is

\[
\frac{X}{X_0} = e^{\mu_{\text{max}} t}
\]

(3)

For cell growth, samples from the bioreactor are taken at 2-hour intervals on the first day and at 4-hour intervals on the second and third days. Mass concentrations are obtained by first measuring the absorbance (at 500 nm wavelength, \( A_{500} \), Milton Roy Spectronic 21D) and converting those values using the conversion factor, \( y \) (g dry cell wt./L) = 0.5x, where \( x \) is \( A_{500} \). Every 8 hours, samples are taken for glucose oxygen (50% of saturation with air), and duration (52 hours). The experiment objectives given to each team are shown in Table 3. The maximum specific growth rate is obtained by applying the Monod equation [6] to the definition of the specific growth rate, \( \mu \), as

\[
\mu = \frac{1}{X} \frac{dX}{dt}
\]  

(1)

where \( X \) is the concentration of cells in the medium (g/L). The Monod equation is

\[
\mu = \mu_{\text{max}} \frac{S}{K_S + S} \frac{A}{K_A + A}
\]

(2)

where \( \mu_{\text{max}} \) is the maximum specific growth rate constant (hr⁻¹), \( S \) and \( A \) are the concentration of glucose and supplemented amino acids, respectively (g/L), and \( K_S \) and \( K_A \) are the half saturation constants (g/L). At the start of the fermentation, \( S >> K_S, A >> K_A \), and therefore \( \mu = \mu_{\text{max}} \) in Eq. (1). The solution to Eq. (1) for exponential growth is

\[
\frac{X}{X_0} = e^{\mu_{\text{max}} t}
\]

(3)

For cell growth, samples from the bioreactor are taken at 2-hour intervals on the first day and at 4-hour intervals on the second and third days. Mass concentrations are obtained by first measuring the absorbance (at 500 nm wavelength, \( A_{500} \), Milton Roy Spectronic 21D) and converting those values using the conversion factor, \( y \) (g dry cell wt./L) = 0.5x, where \( x \) is \( A_{500} \). Every 8 hours, samples are taken for glucose

### TABLE 3
Fermentation Experiment Objectives

1. Determine maximum specific growth rate, \( \mu_{\text{max}} \) (hr⁻¹)
2. Measure glucose consumption (g/L)
3. Measure L-lysine production (g/L)
4. Determine cell growth yield, \( Y_{XX} \)
5. Determine L-lysine production yield, \( Y_{PS} \)

### TABLE 4
Major Steps in the Experiment Procedure for L-lysine Production in Batch Culture

1. Assembly of fermenter and microfilter for steam sterilization
2. Steam sterilization of fermenter and microfilter
3. Media preparation
4. Filter sterilization of culture media
5. Calibration of pH and dissolved oxygen probes
6. Initialize data acquisition
7. Fermentation
8. Sampling for cell, glucose, and L-lysine
9. Analysis of glucose and L-lysine samples
10. Shutdown and clean-up of fermenter
and L-lysine analysis by filtering 5 ml of cell culture solution through a 0.2 µm (polycarbonate, 25 mm dia. Millipore GTTP02500) membrane and into a closed capped vial (20 ml) to remove cells. These samples are then stored in a refrigerator (4°C) until the end of the experiment, when they were analyzed together by the second group of the team. Glucose concentration is analyzed using the hexokinase/glucose-6-phosphate dehydrogenase method (INFINITY Glucose Reagent, Sigma Scientific) and L-lysine concentration by using the saccharopine dehydrogenase assay (Sigma Scientific S-9383). The yield of cell growth on glucose consumed \((Y_{X/s})\) is calculated as \(Y_{X/s} = \Delta X/\Delta S\) and the data are taken over the exponential and deceleration growth stages. The yield of L-lysine produced on glucose consumed \((Y_{P/s})\) is calculated as \(Y_{P/s} = \Delta P/\Delta S\) and the data are taken over the entire fermentation period, but especially during deceleration and stationary stages of cell growth (when L-lysine production occurs). Although different student groups conducted the initiation and sample analyses portions of the experiment, the group that was not “on duty” was encouraged to drop into the laboratory to observe the activities of the other group, and many students did so when their class schedules permitted.

The major steps in the fermentation procedure are shown in Table 4. Table 5 shows the composition of the defined medium for the fermentation per liter of solution. Handout materials for this experiment can be obtained in electronic format (PDF file) by contacting the author at <drshonna@mtu.edu>. Materials available include an overview of the semester-long experiment plan, an introduction to bioprocess safety issues, and detailed steps in the fermentation preparation, start up, and sample analysis.

**RESULTS AND DISCUSSION**

Figure 3 shows a set of results for the cell growth, glucose consumption, and product formation for these experiments using *Corynebacterium glutamicum*. Cell data shows four stages of batch growth: exponential, deceleration, stationary, and declining. Glucose is consumed fastest during the exponential and deceleration stages and more slowly during the stationary and declining stages. L-lysine production is most rapid during the deceleration stage and increases to the greatest amount during the decline stage. This observation is consistent with the metabolic pathway shown in Figure 2, with L-lysine production in *Corynebacterium glutamicum* being greatest after the added amino acids are largely consumed and cell growth ceases, and during the period that concerted feedback inhibition of the L-lysine metabolic pathway is released. The students are made aware of the difference between growth-associated versus non-growth-associated product formation. Figure 3 provides an example of mixed growth-associated product formation—that is, intermediate between the two types. Results from the remaining experiments (for the most part) showed similar trends for the batch culture data.

Table 6 shows the results for all six teams from the semester-long experiment plan. For the 20 g/L initial glucose concentration experiments, the maximum cell concentration decreased (from 9.5 to 4.0 g/L) when the initial amino acid concentration was decreased by 50%, but cell concentration did

---

**TABLE 5**

Composition of Defined Minimal Media for L-lysine Production using *C. glutamicum*.

(All values are per liter of final solution)

- 20 grams D-glucose
- 5 g (NH₄)₂SO₄
- 8 g K₂HPO₄
- 4 g KH₂PO₄
- 0.2 g MgSO₄ · 7 H₂O
- 1.0 g NaCl
- 0.5 g citric acid
- 20 mg FeSO₄ · 7 H₂O
- 50 mg CaCl₂ · 2 H₂O
- 150 mg L-threonine
- 100 mg L-methionine
- 100 mg L-leucine
- 1 mg biotin
- 1 mg thiamine · HCl
- 10 ml 100x trace salts

100x Trace Salts Solution: per liter of distilled water

- 200 mg MnSO₄
- 6 mg H₂BO₃
- 4 mg (NH₄)₂MoO₄ · 4 H₂O
- 100 mg FeCl₃ · 6 H₂O
- 1 mg ZnSO₄ · 7 H₂O
- 30 mg CuSO₄ · 5 H₂O

(pH of this solution adjusted to 2 to avoid precipitation)

---

**Figure 3.** Results for cell growth, glucose consumption, and L-lysine production for initial concentrations of 20 g/L of glucose and base case amounts of amino acid supplements.
not increase (it decreased slightly from 9.5 to 8.5 g/L) as expected from the metabolism shown in Figure 2, when the initial amino acid concentration was increased by 50%. The absence of this additional cell growth may be due to the increase in L-lysine production. An increase in the initial amino acid concentration of 50% did increase the ultimate L-lysine concentration (from 2.09 to 7.5 g/L), whereas a decrease in the initial amino acid concentration did not significantly change the L-lysine concentration.

For the 30 g/L initial glucose experiments, again the maximum cell concentration decreased (from 8.0 to 3.9 g/L) when the initial amino acid concentration was decreased by 50%, but (contrary to the 20 g glucose/L results) the ultimate L-lysine concentration increased (from 2.55 to 10.0 g/L). The results for 30 g glucose/L and 150% amino acid concentration were compromised because the dissolved oxygen probe failed during the run, causing the culture to become anaerobic and changing the cell growth and L-lysine production characteristics. This team proceeded in the same manner as the other teams. They measured cell concentration, plotted a cell growth curve, measured glucose consumption and lysine production, and calculated all growth and yield parameters. The purpose for doing this in this case was to measure effects of anaerobic growth conditions on fermentation performance.

The cell growth yield, \( Y_{xs} \), varied from 0.27 to 0.99 for these experiments, with the exception of the last experiment, which became anaerobic, as mentioned previously. These values are in the range typically found for aerobic culture on glucose and similar growth substrates.\(^{10} \) The highest value violates a carbon mass balance, however, which predicts a maximum biomass yield of

\[
Y_{xs} = \frac{g_{biomass} \cdot 72 gC}{0.5 gC \cdot 180 g_{sugar}} = 0.8 g_{biomass} / g_{sugar}
\]

for typical values for biomass dry weight fraction carbon of 49-51%. Most likely, this erroneous result came from measurement error on glucose, as the cell mass measurement is more accurately obtained. The L-lysine production yield varied over the range of 0.14 to 0.60 for the various experiments.

The results from this experiment plan for cell growth and L-lysine production confirm the student’s prior understanding regarding metabolism for this culture, as shown in Figure 2. Maximum cell growth did decline approximately in proportion to the decrease in the initial amino acid concentration, although it did not increase with increasing amino acid concentration. Additional experiments are needed to reduce uncertainty in measured results, which may help explain the higher-than-possible biomass yield observed in one of the experiments. Enhanced L-lysine production was observed compared to the basecase conditions for two experiments, 20 g glucose/L, 150% amino acid concentration and 30 g glucose/L, 50% amino acid concentration. From the results thus far, however, the exact mechanism for this enhanced production is not yet understood.

Table 6, along with a summary narrative of the results from the entire set of experiments, was developed by the instructor and disseminated by e-mail attachment at the end of the semester to the students who participated in the fermentation experiments. The narrative contained a summary of key results for these fermentation experiments:

1. The supplemental amino acids limit the maximum cell concentration that is achieved during fermentation.
2. Cell growth and L-lysine production appear to occur in separate stages of the fermentation.
3. It is possible to increase L-lysine concentration by the end of the fermentation by altering initial glucose and amino acid concentrations.

This end-of-semester summary provided the cumulative results needed to address the two most important experiment objectives: testing the hypothesis that maximum cell concentration in the fermentation is affected by the initial concentration of supplemented amino acids and identifying whether initial glucose and amino acid concentrations could be altered to enhance L-lysine production.

The Department of Chemical Engineering at Michigan Tech has an assessment program for the evaluation of student learning outcomes. As required by ABET 2000 Criteria, we use these assessments to monitor student proficiency in mastering chemical engineering fundamentals and for improving faculty teaching effectiveness.

In this assessment program there are eight major efforts,
SAFETY CONSIDERATIONS

Safety is integrated into all aspects of the undergraduate chemical engineering laboratory experience at MTU. In the design phase, before any equipment was purchased, a thorough safety review of the bioprocessing equipment, procedures, chemicals, and biological organisms was conducted. The physical and chemical hazards in this laboratory are common to other chemistry or chemical engineering laboratories: contact or ingestion of concentrated HCl and NaOH; flammability hazards; hazards of high-pressure bottled air, O₂, and N₂; and hazards of poor housekeeping.

In addition to the chemistry laboratory safety concerns, Corynebacteria glutamicum is classified as a Level 1 biohazard (the lowest biohazard classification). To mitigate the additional hazards of biological agents, the Center for Disease Control (<www.cdc.gov>—search for biosafety) recommends specific standard practices including:

- Restricting access to the laboratory
- Washing hands with antimicrobial soap prior to leaving the laboratory
- Disinfecting all work surfaces with 75% ethanol after any spill
- Decontamination (by autoclaving or use of 3% bleach) of all cultures, growth media, equipment, and disposables after use

Proper preparation of growth media, sterilization of equipment before use, sterile transfer of growth media into the reactor, and proper inoculation techniques are critical to the success of fermentation, and all these aspects expand the students’ awareness beyond the traditional chemical engineering experience. Couple this with the biosafety program, and students are well prepared to enter this exciting area of the chemical engineering profession.

CONCLUSIONS

A batch fermentation experiment to produce L-lysine was developed for the Chemical Engineering Senior Laboratory at MTU. The experiment objectives and procedures are appropriate for an introductory treatment of batch fermentation processes, microbial growth, and metabolism. A semester-long experiment plan has been implemented to test for the effects of initial amino acid and glucose concentrations on cell growth and L-lysine production in long-term experiments (52 hours).

The direction of tasks between the two student groups in each team appears to result in a reasonable level of student effort in this long-term experiment. Judging from the oral and written reports, the students appear to understand the fundamental biochemical principles (provided during a pre-laboratory one-hour orientation and from handout materials) at a level sufficient to interpret experimental results. Considering that most students had little or no prior biochemistry education, this outcome is viewed as positive.

ACKNOWLEDGMENTS

Funding to develop this experiment was provided by a National Science Foundation Instrumentation and Laboratory Improvement grant (Proposal No. 97-50570), by the James and Lorna Mack Endowment Fund, and by the Davis W. Hubbard Memorial Fund at Michigan Technological University. Several graduate and undergraduate students were involved in the development of these experiments, including Dale Clark, Amber Kemppainen, Renu Chandrasekaran, Geoffrey Roelant, and Eileen Kim. Helpful comments by three anonymous reviewers were greatly appreciated.

REFERENCES

FACTORS INFLUENCING THE SELECTION OF CHEMICAL ENGINEERING AS A CAREER

DAVID C. SHALLCROSS
University of Melbourne • Melbourne, Victoria 3010, Australia

Around the world a range of strategies has been proposed and adopted in an effort to attract more students into chemical engineering. These strategies range from distributing brochures, videos, and interactive CD-ROMs to secondary school careers teachers, to running activities for either the school students or their mathematics and science teachers.

In Australia in the early 1990s, the Joint Victorian Chemical Engineering Committee commissioned a short video, “This is Chemical Engineering,” that was later distributed to all secondary school careers teachers, and in 1997, to celebrate the 75th anniversary of the Institution of Chemical Engineering, that UK-based body prepared and distributed a CD-ROM aimed at secondary school students. More recently the Institution of Chemical Engineers has established an innovative website aimed at attracting secondary school students into the profession (found at <www.whynotchemeng.com>). The American Institute of Chemical Engineers has a similar, but less interactive, site at <www.aiche.org/careers/>. Some universities, such as North Carolina State University, run summer engineering camps for school students and their teachers.

Rather than targeting the students, another strategy involves working with secondary school math and science teachers to raise the profile of the profession in the secondary school community. The Faculty of Engineering at the University of Melbourne has followed this strategy since 1994. In that year, the faculty began running one-day seminars for secondary school math and science teachers to introduce them to engineering. More recently, a book (jointly written by a chemical engineering academic and four practicing secondary school math teachers) has been published that introduces teachers and students of years 9 to 11 (ages 15 to 17) to real engineering applications of mathematics. The problems presented to the readers relate to the design of a bulk liquid chemical storage facility, i.e., a tank farm. As another strategy, the Tufts University Center for Engineering Educational Outreach has been involved in a project pairing graduate-level engineering and computer science students with secondary school classroom teachers.

But, which of these strategies is most effective? While engineering graduates have been surveyed to identify the factors that led them to study engineering at the undergraduate level or at the postgraduate level, and to identify the main work activities in their professional careers, no studies have been reported in the literature that investigate the career choices of currently enrolled chemical engineering undergraduate students.

This paper reports on the results of a survey aimed in part at identifying the most effective strategies. Between October 2000 and October 2001, over 2,500 undergraduate chemical engineering students studying at 15 universities in seven countries were surveyed. The survey sample was drawn from all year levels and included students who had left their home country to study. The aims of the two-page survey were three-fold:

- To investigate student perceptions of the chemical engineering profession
- To investigate the key factors that influenced the student’s decision to become a chemical engineer

David Shallcross is Associate Professor in the Department of Chemical and Biomolecular Engineering at the University of Melbourne and is Associate Dean (International) of the Faculty of Engineering. The author of three books, he is active in the secondary school community developing teaching material aimed at raising the profile of the engineering profession for school students.

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To determine which of a list of fifteen industrial sectors the students most and least want to work in upon completion of their degree

This paper examines the key factors that influenced the students to choose chemical engineering as their profession. The results from the other sections of the survey are published elsewhere.[13,14]

SURVEY METHODOLOGY

The survey consisted of a single-sheet, two-page form prepared in English, German, Russian, and Vietnamese. It was only given to students currently enrolled in an undergraduate chemical engineering course. The students were asked to identify their gender, their grade level, and whether or not they were studying in their own country. The questions asked of students are shown in Table 1.

Some thirty universities in a range of countries that included Australia, Canada, Germany, New Zealand, Russia, Thailand, the United Kingdom, the United States, and Vietnam were contacted and asked to participate in the survey. A number of universities declined for a variety of reasons, including university policies against conducting external surveys and concerns over the privacy rights of their students. Fifteen of the sixteen universities that agreed to participate are listed in Table 2 (the University of Hanoi also participated in the survey, completing about 500 forms, but they were lost by the Vietnamese postal service and were not received for processing.) Table 3 summarizes the number of respondents by gender and national origin. In all countries except Vietnam, the English-language version of the survey was used.

There is a total of eleven university chemical engineering departments in Australia and New Zealand, so the four participating in the survey provided a statistically significant sample of the student population from this region. The same is true for the United King-

| TABLE 1 |
| Survey Questions |
| Indicate the extent to which you agree or disagree with these statements: |
| • Chemical engineering is a well-paid profession. |
| • Chemical engineering offers scope to express my creativity. |
| • I am happy with my choice of chemical engineering as a career. |
| • Chemical engineers are concerned with sustaining/enhancing the quality of our environment. |
| • Chemical engineering is important to the well-being of society. |
| • Chemical engineering will allow me to work and travel internationally. |
| • Chemical engineering is different to what I thought it was when I applied to enter the course. |
| • Chemical engineering is a well-respected profession. |
| • Chemical engineering is of more value to society than other forms of engineering. |
| • Chemical engineers need communication skills of a high standard. |
| • I would recommend others to study chemical engineering. |
| • I expect that within ten years of graduating, I will have moved out of engineering into a management role. |

I chose chemical engineering because

• I was inspired by a member of my family to study chemical engineering. |
• I was inspired by a "role model" chemical engineer (not a family member) whom I admire. |
• I really liked chemistry at school. |
• Chemical engineering is involved in a range of diverse industries. |
• I wanted to do engineering, but didn’t like/take physics at school. |
• I wanted to do engineering, but the other engineering disciplines didn’t appeal to me. |
• A chemistry teacher at my school triggered my interest in chemical engineering. |
• A careers teacher at my school suggested that I consider chemical engineering. |
• I was inspired by visiting a tertiary information session/event. |
• I attended an engineering camp/summer school type event. |
• Chemical engineering is a "clean" form of engineering. |
• I was told to study chemical engineering by a family member. |
• I will be able to make a positive difference in caring for the environment. |

---

| TABLE 2 |
| Summary of Survey Respondents |

<table>
<thead>
<tr>
<th>Gender</th>
<th>Not Stated</th>
<th>Student Origin</th>
<th>Not Stated</th>
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</thead>
<tbody>
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</tr>
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</table>
To illustrate how the survey results might be analyzed, consider the following example. Of the 220 local Canadian students surveyed, 216 non-zero responses were recorded to the statement above. Of these, 76.4% indicated no influence, 19.9% indicated some influence, and just 3.7% indicated a strong influence. The average score for this statement is 1.27 and is based only on the non-zero responses.

The questions and statements used in the survey were carefully selected after consultation with students enrolled at Australian universities. The thirteen statements relating to the choice of chemical engineering as a career and Table 4 presents the equivalent information numerically, but also classified by gender.

Several important points arise from the results:

- A third of students admitted to being inspired by a member of their family. Responses to the statement "I was inspired by a member of my family" are shown in Figure 2. Overall, no more than 11% in each country admitted to being strongly influenced to take chemical engineering by a family member. In the U.S., however, significantly more female students were influenced by this factor (15.4%) than were male students (7.4%). Over half the female students admitted to some form of influence, while two-thirds of the male students were not influenced at all by family members.

- Very few students were influenced by non-family role models. In Australia and New Zealand, nearly 90% of respondents said they were not influenced at all by this factor, while in Vietnam, nearly 40% were influenced to some degree.

- One of the two most important factors identified by the

<table>
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<th>Country</th>
<th>Total</th>
<th>Male</th>
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<th>Not Stated</th>
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<td>82</td>
<td>168</td>
<td>159</td>
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</table>


In the survey, students were given statements on why they chose to study chemical engineering (such as "I really liked chemistry at school") and were asked to indicate the level to which this influenced their decision. The survey responses were scored "strongly influenced" 3, "some influence" 2, "no influence at all" 1, no response 0, and more than one response 0. To illustrate how the survey results might be analyzed, consider the

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Fall 2003

survey was, not surprisingly, that the students liked chemistry at school. Nearly 70% of the U.S. respondents said they were strongly influenced by their school chemistry experiences, with just 5.1% admitting that they were not influenced at all. The percentages of Australian and New Zealand, Canadian, UK, and Vietnamese students who were not influenced at all by this factor were 12.3%, 18.0%, 12.7%, and 17.4%, respectively (see Figure 3). There was little difference in responses between genders.

The second major factor identified by the survey was that students perceived that chemical engineering is involved in a diverse range of industries. Care must be taken, however, in interpreting the responses to this particular statement. Of the thirteen statements in this section of the survey, all but two (including this one) were framed directly in response to the opening statement, “I chose chemical engineering because...” Thus, it is possible that students responded to this statement not in terms of whether or not they were influenced by it to study chemical engineering, but whether they believed the statement to be true. Nonetheless, the fact that chemical engineering has application across such a diverse range of industries should be emphasized when recruiting students into the profession’s courses. Across the five university groupings, the percentage of students who identified that the statement “I wanted to do engineering but didn’t like/
take physics at school" played no part in the selection of chemical engineering as a career ranged from 58.0% in Vietnam to 74.3% in the UK. In Australia, New Zealand, Canada, and Vietnam, around 15% of students were strongly influenced by this factor (see Figure 4). There were differences between the genders in all countries, but particularly in the UK, where just 8.1% of males were strongly influenced by this factor, while for females it was 23.0%.

More female students than males were strongly influenced by the fact that they wanted to study engineering but the other disciplines didn't appeal to them. In Canada, 17.6% of males and 34.1% of females were strongly influenced by this factor, while the corresponding figures for the UK were 19.8% and 31.0% for males and females, respectively. Of the 70 students from Australia and New Zealand who were strongly influenced in this respect, only five indicated they were not influenced at all. When coupled with the responses to the preceding statement regarding physics, it is apparent that chemical engineering owes a significant proportion of its appeal to the fact that of all the major engineering disciplines, it is the one in which a sound foundation in physics is the least important. Kumagai conducted focus group meetings with over 500 female undergraduate students at eight different universities[13] and found that women who had chosen chemical or environmental engineering did so because of negative experiences in physics at secondary schools. Figure 5 presents the distribution of responses for the five regional groupings.

In Australia, New Zealand, and the United Kingdom, the influence of a chemistry teacher was relatively low compared to a much greater influence in Vietnam (see Figure 6). Just one-third of all Australian and New Zealand students responded that they were influenced to some extent by their chemistry teachers. This is all the more surprising because nearly 90% of these students said that they really liked chemistry at school. These statistics suggest that in all countries other than Vietnam, significant opportunities exist to work with chemistry teachers to raise the profile of chemical engineering as a profession. This could be achieved by running professional development sessions for chemistry teachers where chemical engineering is showcased, or by developing material for the secondary school chemistry classroom that illustrates how chemical engineers use basic concepts taught in chemistry in real-life applications.
School careers teachers play a relatively insignificant role in steering students toward chemical engineering (see Figure 7). In North America, 87% of all respondents were not influenced at all by them, while in the UK they were more effective, having had some level of influence over 36% of the students. It is possible that many of the North American respondents misunderstood the term “careers teachers” as this is not a term in common use there. In other parts of the world, the term is well understood. One conclusion that can be drawn from these results is that the institutions and professional bodies in all countries should work more closely with careers teachers.

Many educational institutions put a lot of effort into events such as university open days. The results presented in Figure 1 and Table 4 show that in Vietnam, in particular, these events are effective, with 19.8% of Vietnamese respondents being strongly influenced and 34.6% influenced to some degree. At the other extreme, only 5.1% of U.S. students were strongly influenced by such events, compared to 76.4% who were not influenced at all. It should be noted, however, that the term used in the survey, “tertiary information session/event,” may have been misinterpreted so that respondents did not consider it to encompass university open days and the like.

One of the biggest differences in responses between genders was observed for the role of the engineering camp/summer school-type event. Just 20% of male UK students indicated they were influenced to some extent by such events, while nearly 45% of the female UK students were influenced. A similar difference in responses between genders was observed for U.S. students. In Australia, Canada, and New Zealand, such events had very little influence.

“Chemical engineering is a clean form of engineering” is the second of the two statements not directly framed in response to the opening statement. The responses indicate that this perception has relatively little influence on the selection of chemical engineering as a career, with less than 7% of students in each of the groupings being strongly influenced by this factor. Of those few who were strongly influenced by this perception, however, some two-thirds were also strongly influenced by the perception that as chemical engineers they will be able to make a positive difference in the environment.

Very few respondents chose to study chemical engineering because they were told to by a family member. The greatest degree of influence occurred among Vietnamese respondents. Across all countries, females admitted to being more strongly influenced than males.

The perception that the respondents will be able to make a positive difference in caring for the environment had relatively high average scores across all five groupings. In Vietnam, nearly 40% of the respondents indicated that they were strongly influenced by the perception. Across most country groupings, females were influenced significantly more than male students by this perception.

In Australia, high proportions of students are enrolled in combined degree programs in which they can pursue two degrees simultaneously. These programs have been described more fully elsewhere. No statistically significant differences in the factors leading to the selection of chemical engineering were observed between students currently enrolled in single and combined degrees.

No statistically significant differences were observed between students enrolled in different year levels. This is as expected since the factors leading to a student’s selection of a particular course should not vary significantly in the space of five years.

CONCLUDING REMARKS

The results of this international survey clearly show the factors that influence a student to study chemical engineering differ between countries. Some of these differences may arise due to cultural factors and historical influences. Vietnamese students are more strongly influenced in their choice of chemical engineering than students in other countries by their chemistry teachers, by tertiary information events, and by the perception that they will be able to make a positive difference to the environment. In the UK, the role of careers teachers is much more important than in Australia, New Zealand, or Canada.

Gender issues are also important, with the responses from male and female students differing considerably in several instances. A number of workers in the past have studied the gender issues related to course selection at school. Lewis[17] stated

*It is at the crucial adolescent age when females seek interrelatedness and males seek independence that we ask students to make their subject choices. Girls who choose the physical sciences or engineering not only have to show a strong sense of independence by choosing a nontraditional subject, they are also asked to choose a set of math and science subjects which are characterised as abstract laws disconnected from their social and physical worlds. Boys, on the other hand, can make a decision in tune with their peer group, and overlapping their need for emotional separation through disconnected abstract laws.*

---Continued on page 281.
One of the joys of teaching a course on powder technology is the abundance of quick and simple experiments that can be used in lectures to demonstrate the fundamental phenomena being discussed. These can be used as breaks part way through a lecture or as an interest-arousing introduction to a new topic. Demonstrations can be used to highlight the often counter-intuitive behavior of powders by asking the students to break into groups and try to predict a priori how they expect a given system to behave. The often quite different behavior that they subsequently observe will then challenge them to understand the causes of their misconceptions and arouse their interest in the lecture material.1,2

There are more than enough such demonstrations to fill a spot in every lecture of a one-semester introductory course on powder technology. Most, however, are referred to only in passing in references scattered throughout the literature3-6 or are passed on by word-of-mouth from one practitioner to another. Klinzing7 has provided a partial list of such demonstrations, and a recent CD by Rhodes and Zakharis8 contains video clips of many others.

This paper seeks to provide a comprehensive compilation of demonstrations to act as a reference for new instructors in particle technology. Demonstrations related to wet-powder systems are presented first, followed by dry-powder systems. Wet-powder system behavior covered includes single-particle settling, hindered and lamella settling, sedimentation, the effect of surface chemistry on slurry rheology, powder wetting, and wet-granule coalescence. Dry-powder system behavior covered includes flow from hoppers, percolation and elutriation segregation, the “Brazil-nut” effect, surface friction, and powder compaction. Where possible, the source of the ideas presented is acknowledged, either by reference to a publication or mention of the person who first told the authors. Many of these ideas have been around so long, however, that it is difficult to identify their origin, and we apologize in these cases for not acknowledging their original source.
tling times for a 40-cm long tube are of the order 0.4 s, which is less than the approximate 1 sec and 10 sec observed in practice. Clearly, buoyancy effects alone do not explain the speed at which the marbles fall.

At this stage (if they have not already done so), some students may recall the concept of viscosity and fluid drag from their previous fluids courses. This can lead to a brief review of drag coefficients, terminal velocities, etc. For the marble in glycerol, the Reynolds number is low and Stokes’ law (\( C_D = 24/Re \)) applies. Hence, the terminal settling velocity \( V_T \) of the marble is given by

\[
V_T = \frac{(\rho_p - \rho_L) d^2 g}{18 \mu}
\]

where \( \rho_p \) and \( \rho_L \) are the density of the particle and liquid, \( d \) is the marble diameter, \( g \) is gravitational acceleration, and \( \mu \) is the fluid viscosity.

For the marble in water, the Reynolds number is of order \( 10^5 \), giving a drag coefficient of approximately \( C_D = 0.44 \). The terminal settling velocity is given by

\[
V_T = \frac{4(\rho_p - \rho_L) dg}{3\rho_L C_D}
\]

Thus, the difference in viscosity between glycerol (\( \mu \approx 1 \) Pa·s) and water (\( \mu = 0.001 \) Pa·s) can be shown to be the major cause of the difference in their settling velocities.

Some students may also think of another cause for the slower than expected fall of the marbles, namely hindering caused by the back flow of displaced liquid up the tube walls as the marble moves past. This is illustrated in the next demonstration.

**Hindered and Lamella Settling (in-class demonstration)**

Hindered settling can be illustrated using a pair of perspex tubes filled with the water, the first containing only a single small bead and the second a large group of identical beads.

The settling rates of the two systems can then be compared, to illustrate how the presence of many particles reduces the settling speed. Explain how settling is hindered by the need for the displaced water to flow back up through the bed of particles (see Figure 1a); then ask the class to think of ways to increase the rate of particle settling.

One way to accelerate settling is to tilt the tube slightly so that particles have only a short distance to fall to reach the tube wall, where they can then slide down quickly as the displaced water flows unhindered above (Figure 1b). This illustrates how lamella settlers operate. Another method is to shake the tube in a horizontal circular motion while keeping it vertical. The centrifugal force moves particles to the wall, leaving the center of the tube free for displaced water to flow upward, thus allowing the particles to settle more quickly down the sides (Figure 1c). This is similar to what happens inside a hydro-cyclone.

**Sedimentation and Flocculation (in-class demonstration)**

The different types of sedimentation behavior can be easily demonstrated by filling three tall jars with Type I, Type II, and colloidal (non-settling) particle suspensions. Shake the jars at the start of the lecture and point out the different behaviors. Type I suspensions are those that form three zones during settling—a clear liquor above the settling particles (zone A), a suspension of particles of the same concentration as the initial suspension (zone B), and a settled bed at the base (zone S). During settling, the interface between zones A and B falls and the interface between zones B and S rises, until the two meet and zone B disappears.

Type II suspensions form four zones during settling. In addition to zones A, B, and S, there is a zone of variable concentration (zone E) that forms between zones B and S. Colloidal particles do not settle out at all. Toward the end of the lecture, once students are convinced that the colloidal particles are not going to settle, a flocculant can be mixed into the suspension to demonstrate the resultant dramatic improvement in settling behavior.

**Sedimentation and Flocculation (laboratory module)**

A laboratory module based on particle settling is also possible. Give the students three or four samples of silica of different average particle size ranging from about 1 micron to about 250 microns. The size distributions should be monomodal and less than one decade in breadth. Prepare 250 ml of a suspension of 3 wt% solids for each powder in distilled water in 150-ml graduated cylinders. Adjust the pH to 8.0 with NaOH so that the silica is well dispersed. Shake the cylinders and observe the sedimentation. Measure the time required for the first noticeable formation of the sediment bed. Measure the height of the interface between the clear supernatant and the suspension as a function of time.

Students will notice that the micron-sized silica does not settle appreciably in the time available. Mention that for par-
icles smaller than about 0.1 microns, Brownian motion dominates gravitational settling so that a stable suspension results. Use a suitable cationic polymer to flocculate the suspension so a clear supernatant results.

The students should calculate the size of the largest particles in the sample assuming that the time for the first noticeable sediment bed to form corresponds to the time that the largest particles settle the distance from the top of the tube to the bottom. Using that velocity and Stokes’ law or Newton’s law, the size of the largest particles can be calculated. They should also calculate the size of the smallest particles based on the velocity of the suspension/clear supernatant interface. Then provide them with the measured particle size distributions of the silica samples and ask them to compare their calculated largest and smallest particle sizes with the size distribution data provided. The comparison is surprisingly good.

**Interparticle Force Effects on Colloidal Suspension Rheology**

(laboratory module)

Many chemical engineers are not trained to consider how the chemical nature of the fluid medium can influence the rheological behavior of a suspension. pH is one of the easiest properties of a slurry to measure on-line and it can also have a dramatic effect. The students measure the yield stress of a 0.40 volume fraction of solids zircon suspension over a range of pH values. The average size of the zircon is about 6 microns, so the interparticle surface forces are important in determining the rheological behavior. The density of zircon is 4400 kg/m³. The yield stress can be measured by the slump method.\(^{(11)}\) In this method, the paste-like suspension is filled into a cylinder on a flat surface and the cylinder is lifted off the suspension. The resulting slump height is measured (see Figure A1). The yield stress is related to the slump height by

\[ \tau_v = \frac{pH}{2} \left( 1 - \frac{s}{H} \right) \] \hspace{1cm} (A1)

where \( \tau_v \) is the yield stress, \( p \) is the suspension density, \( g \) is the gravitational acceleration (9.8 m/s²), and \( H \) and \( s \) are indicated in Figure A1.

The students should measure the yield stress of the suspension at pH values of approximately pH 7, pH 6, pH 5, pH 4, and pH 3. Use HCl and NaOH to adjust the pH, being careful not to overshoot the pH and come back since this will add salt to the suspension and thus affect the interparticle forces and thus the yield stress. Make sure the suspension is well mixed. The zeta potentials of the powder as a function of pH can be provided to the students as shown in Figure A2. Ask them to compare the measured yield stress values with the zeta potentials. They should comment on the behavior in their report.

**Abbreviated Laboratory Report:**

Figure A3 is a photo of the slump test being performed by one of the authors. The density of the suspension can be calculated as

\[ \rho_{sus} = \rho_{zircon} + \rho_{H_2O} \]
\[ \rho_{sus} = 0.4 \times (4400 \text{ kg/m}^3) + 0.6 \times (1000 \text{ kg/m}^3) = 2360 \text{ kg/m}^3 \]

The initial cylinder height (H) was 0.103 m. The slump (s) was measured with a ruler over a range of pH values from 3 to 7. The measured slump was used to calculate the yield stress (using Eq. A1). The yield stress is plotted against pH in Figure A4. The maximum yield stress correlates with the isoelectric point (where the zeta potential is zero). At this pH, only van der Waals attraction is operating between the particles creating a strong attraction and thus a high yield stress. The yield stress decreases as the pH is moved away from the isoelectric point. This is because as the charge on the surface of the particles increases, the electrical double layer repulsion also increases—thus reducing the magnitude of the attraction and thus the yield stress. See Shaw,\(^{(12)}\) Hunter,\(^{(13)}\) or Johnson, et al.,\(^{(14)}\) for more details.

![Figure A1. Dimensions used in calculation of yield stress from slump test.](image1)

![Figure A2. Zeta potentials of zircon.](image2)

![Figure A3. Slump test in progress.](image3)

![Figure A4. Yield stresses of zircon.](image4)
bed surface quickly are more likely to form individual nuclei—hence controlling the drop size controls the granule size. Slow penetration can lead to pooling of liquid on the powder surface, resulting in widely sized initial nuclei and widely sized final product.\textsuperscript{[15]}

The rate of penetration of a liquid into the pores of a powder bed can be estimated by equating the capillary pressure driving force from the Young-Laplace equation

\[ \Delta P_{\text{cap}} = \frac{2 \gamma_{LV} \cos \theta}{r} \]  

with the viscous resistance to laminar flow predicted from the Hagen-Poiseuille equation

\[ \Delta P_{\text{vis}} = \frac{8 \mu u l}{r^2} \]  

to give a form of the Washburn equation

\[ u = \frac{d l}{d t} = \frac{r \gamma_{LV} \cos \theta}{4 \mu} \]  

where \( u \) is the liquid velocity, \( r \) is the effective pore radius, \( \gamma_{LV} \) is the liquid-vapor surface tension, \( \theta \) is the solid-liquid contact angle, \( l \) is the length of pore filled, and \( \mu \) is the liquid viscosity.

The effects of the parameters in Eq. (5) can be demonstrated by asking students to measure the penetration times of drops of water, honey, and alcohol onto a number of different powder beds, e.g., coarse and fine sugar, ground pepper, and parmesan cheese (see Figure 2).\textsuperscript{[16]} The coarse and fine sugar demonstrate the effect of pore size \( r \). The rate of liquid penetration is approximately proportional to the particle size. Hence, the water penetrates the fine sugar more slowly than the coarse sugar. (Note: if an alternative powder that is insoluble in water is available in two different particle sizes, this may be preferable to using sugar.) The water and honey demonstrate how increasing viscosity \( \mu \) slows down the rate of penetration. The water and alcohol on the cheese and pepper demonstrate the important effect of contact angle \( \theta \). Water does not wet or penetrate into either of these two powders, but alcohol wets both powders because it has a lower contact angle due to its lower surface tension, as seen by a force balance at the contact line between the three phases (the Young-Dupre equation)

\[ \cos \theta = \frac{\gamma_{VS} - \gamma_{LS}}{\gamma_{LV}} \]  

where the subscripts \( V \), \( S \), and \( L \) refer to the vapor, solid, and liquid phases, respectively.

A more comprehensive predictive model for the penetration time of a liquid drop onto a powder surface is presented by Hapgood, \textit{et al.}\textsuperscript{[15]} This could form the basis of a laboratory module for students in more advanced powder technology subjects where they would be required to measure the powder size and bed porosity.

**Granulation Coalescence Behavior (in-class demonstration)**

Wet granulation is performed by spraying a liquid binder onto an agitated powder mass. There is great interest in being able to predict the rate at which these granules grow as they are agitated. This depends on how likely it is for granules to coalesce during collisions of varying velocity.

In more advanced powder technology subjects, students may be introduced to two of the models available for predicting wet-granule coalescence. The Ennis model considers the collision of two equi-sized elastic spheres of radius \( r \) colliding head-on at a relative speed of \( 2u \).\textsuperscript{[17]} Each sphere is surrounded by a layer of fluid of viscosity \( \mu \) and thickness \( h \). The surface of each sphere has a roughness of \( h_r \), which limits how close they can approach together. The spheres have a coefficient of restitution, \( e \), and a density, \( \rho \). Solving Newton’s second law of motion, it is predicted that coalescence will occur when the viscous Stokes number, \( St_v \), is less than some critical viscous Stokes number, \( St_v^* \), where

\[ St_v = \frac{8 \mu u}{9 \mu} \quad \text{and} \quad St_v^* = \left(1 + \frac{1}{e} \right) \left(\frac{h}{h_a}\right) \]  

This model predicts that reducing the impact speed acts to increase the likelihood of coalescence. This behavior can be demonstrated by dropping a rubber ball from different heights onto a flat surface coated with a layer of honey. Below a threshold impact velocity (release height), the ball will not rebound.

Liu, \textit{et al.}\textsuperscript{[18]} model colliding granules as elastic-plastic spheres that are initially surface dry, but then have liquid squeezed to the surface during collisions. This model predicts that low-velocity collisions are less likely to result in coalescence. This is because very little permanent plastic deformation occurs, and hence the area of contact formed be-

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**Figure 2.** The non-wetting behavior of drops of water (front row) and sugar solution (middle row) compared with the rapid wetting of alcohol (back row) on a bed of grated parmesan cheese. Dye added to liquids to enhance visibility.
Funnel flow by using an hourglass arrangement with a deformable material will flow through the steep-angled hopper in mass flow and through the shallow-angled hopper in funnel flow. Fan[3] extends this idea by connecting the two hoppers by a long straight pipe. This column then acts as a standpipe, exhibiting regions of both moving bed transport and suspension transport of the solids.

**Consolidation Effects of Powder Flow**

*(in-class demonstration)*

One important aspect of powder technology that should be stressed to students is that, unlike most fluids, the behavior of powder systems is history-dependent. The effect of consolidation on flow behavior can be demonstrated by using some dish-washing powder and a funnel (the end of a plastic drink bottle works fine). Pour the powder into the funnel and when the exit is opened, then it will flow out easily. But if the powder is poured into the funnel and tapped before the exit is opened, it will have consolidated and no flow will occur when the exit is opened.[20] Mention should be made that other factors besides consolidation can also cause powder properties to change with time, such as capillary condensation, re-crystallization, and solid-state diffusion causing bonding at interparticle contacts.

**Particle Dilation** *(in-class demonstration)*

Osborne Reynolds[21] demonstrated shear-induced particle dilation using a manometer attached to a rubber bag filled with saturated sand. This experiment can be repeated using a clear plastic drink bottle (the type with the straw built into the cap so that it is easy to use while running or bike riding). Tightly pack the main bottle cavity with saturated sand and then top off with water until the water level reaches part-way up the tube. Ask students what will happen when the bottle is squeezed lightly. Counter to intuition, the water level actually drops. This is because the sand must dilate in order for particles to slide over one another. Water flows back into the powder bed as it dilates. This dilation behavior explains why sand “dries up” around your foot as you walk along the beach near the water’s edge. Water is sucked away from the surroundings into the dilated sand matrix. When you lift your foot, this excess water then causes the sand to temporarily liquefy as the load is relaxed.[e.g.,22]

**Wall Friction** *(in-class demonstration)*

Powder bed behavior is different from that of a Newtonian fluid. In a fluid, some flow is always initiated when a shear force is applied, but powder beds offer a finite resistance to shear forces. This ability of a powder bed to support large loads can be demonstrated by asking students to push or pull a plunger up a tube that is gradually filled with more and more particles. Eventually, a stage of filling is reached beyond which they can no longer move the plunger—the force they are exerting is totally transferred by the particles to the wall of the tube. The force being exerted can be made visually evident by either including a spring balance on the pull cable[7] or by attaching a large spring on the shaft used to push the plunger up the column.[3] The implications of this behavior for the distribution of stresses on hopper walls and

**Dry-Powder Systems**

**Hopper Flow** *(in-class activity)*

A good hands-on introduction to a set of lectures on hopper flow is to split the class into groups of 2-4 students each and supply each group with some thin cardboard, paper, overhead transparencies, masking tape, scissors, a beaker of sand, and a pan (to prevent spilling sand all over the classroom floor). Give them 10 to 15 minutes to build a funnel (hopper) that must discharge a set mass of sand in a set time (starting full). Make up a hopper beforehand to check that the time limit is reasonable—try to set a required time that is long enough so that in trying to slow down the flow, the students will encounter problems such as arching or rat-holing. Offering an incentive such as a large chocolate bar as a prize for the group that gets closest to the set time adds some competitive spirit and fun to the exercise.

Wander between the groups as they try different designs and ask them what the design parameters are (hopper angle, opening size, and possibly the wall material), how the material is flowing (mass or funnel flow), and what problems they are encountering (e.g., arching and rat-holing). Some groups may resort to things such as tapping or stirring the hopper in order to promote flow—discuss the practicalities and costs associated with this in an industrial setting.

**Funnel Flow and Mass Flow** *(in-class demonstration)*

The two main types of flow from hoppers are mass and funnel flow. In mass flow, the entire powder bed is in motion as the bin discharges. The first material put into the bin is also the first to come out. In funnel flow, material slips from the top surface down through a rat-hole in the center of the bin. The material at the bin walls is static—hence the first material put into the bin is often the last out of it. Jenike and Johanson[19] demonstrate the difference between mass and funnel flow by using an hourglass arrangement with a different hopper angle in each half (photograph can be found in reference 7). If the hopper angles and material are chosen correctly, the material will flow through the steep-angled hopper in mass flow and through the shallow-angled hopper in funnel flow.
Segregation During Hopper Flow (in-class demonstration)

Another counter-intuitive behavior of powders is that flow and agitation often cause segregation, rather than mixing. Segregation during discharge of material onto a stockpile or into a hopper is a well-known phenomena. Many workers have used transparent 2D hoppers to demonstrate the “herring-bone” pattern formed due to a combination of percolation of fine particles and the lower angle of repose of the coarse particles (see Figure 3). The small particles percolate between the larger ones and this causes the fine ones to become concentrated in the center of the bed. During the periodic avalanches, large particles tend to roll further down the sloped surface of the bed because of their higher inertia and lower angle of repose. During these avalanches, the fine particles tend to settle out along the way. This causes the larger particles to become concentrated at the base of the pile and also gives rise to the alternate bands of fine and coarse material.

A third, and less-often demonstrated mechanism of segregation is the elutriation or fluidization of ultra-fine particles in the upflowing air displaced by the downflowing solids. This can result in the ultra-fine particles settling out after the other particles and forming a layer on top of the heap. With an airtight 2-D hourglass arrangement and correct choice of particles, elutriation and percolation segregation phenomena can both be demonstrated simultaneously in the same apparatus. Figure 3 shows the demonstration midway through the discharge process. The back flow of air has elutriated the ultra-fines from the material flowing through the opening. The ultra-fines have instead formed a fluidized bed in the upper hopper. As a result, they are the last particles to flow from the hopper and hence they deposit on the top surface of the heap and flow down to the base at each edge.

Before performing this demonstration, the students should be asked to predict where in the heap they think the different size fractions of material will be preferentially deposited. Then they can compare their predictions with the final result. Discuss the difficulties this behavior causes in obtaining representative samples from a poured heap of granular material. Representative samples can only be obtained by sampling at random intervals of time the full cross-section of a powder stream when it is in motion.

Vibrational Segregation (in-class demonstration)

The well-known “Brazil nut” effect can be easily demonstrated by covering a steel ball bearing with sand and then vertically tapping the container. The steel ball will rise to the surface, in spite of its greater density. The cause of this phenomena is not fully understood, but is believed to be linked to the inertia of the object, causing it to “punch through” the expanded bed during the upstrokes, whereas the packing of the powder prevents it from descending during the downstroke.

Shinbrot and Muzziol suggest a variation to this demonstration. If a low-density object is also added to the container, then the behavior of the two objects varies depending on whether the container is shaken horizontally or vertically. Under vertical vibrations, the steel ball rises and the low-density object sinks. Under vigorous horizontal vibrations, the steel ball sinks and the light object rises! The cause of this reversal is unclear, but is probably due to the bed dilating and becoming fluidized during horizontal vibration. The class can be asked to predict beforehand which of the two objects will rise or sink when the jar is “shaken” (without specifying how). Then the instructor can deliberately shake the jar in a direction that gives a result counter to the majority class opinion, in order to arouse their interest.

Fluidization (in-class demonstration)

Fluidization can be demonstrated in the classroom using a small bed connected to a portable compressor, or if the bed is small enough, a willing volunteer’s lungs. Behavior that can be displayed includes the way the fluidized bed remains level as the bed is tilted and the floating and sinking of objects of different density when the bed is fluidized. This can be contrasted with the behavior of these objects in the bed when it is vertically vibrated (see Vibrational segregation above).

Bubbling behavior can be demonstrated by filling a long tube most of its length with a Geldart Group A powder. Inverting the tube will result in a slug slowly rising up the length of the column. Again, students could be asked beforehand...
to predict what will happen when the tube of fine powder is inverted. Many may expect the powder to move as a solid plug from one end to the other.

**Flow Improvement Due to Powder Agglomeration**

*(in-class demonstration)*

The dramatic improvement in the flow properties of granulated versus ungranulated materials can be demonstrated by setting two hoppers side-by-side, one with the raw fine powder and the other with the same powder after it has been granulated. When inverted, the raw powder arches and does not flow without tapping, whereas the granulated product flows freely (see Figure 4). Small batches of granules for use in this demonstration can easily be prepared at home in a domestic food processor.

**OTHER RESOURCES FOR POWDER TECHNOLOGY EDUCATION**

If you do not have the resources or time to build and perform these demonstrations, many of them are shown as video clips on a CD produced by Rhodes and Zakhari,[6] An expanded version of this CD is due out soon that will include interactive problems.

The Particle Technology Forum of the American Institute of Chemical Engineers has established a website with many good educational resources for particle technology.[8] For ideas on how to construct and structure an introductory course on powder technology, we suggest reading the papers by Chase and Jacob,[3] Donnelly and Rajagopalan,[4] and also the textbook by Rhodes[23] that was written specifically with the purpose of being an introductory undergraduate textbook.

**CONCLUSIONS**

Instructors of powder technology courses have no excuse for not using visual, hands-on demonstrations to introduce a little more variety and interest to their teaching. Most of the demonstrations mentioned in this paper can be built at little cost using materials readily available in most engineering departments. No expensive or hazardous chemicals are needed, and most of the powders can be found at your local beach or supermarket. Asking students to guess the powder behavior before the demonstration is performed is an effective tool for engaging their interest.

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Perhaps the most important conclusion that can be drawn from this survey relates to the different extent that an enjoyment of chemistry at school and the role of chemistry teachers influences students to study chemical engineering. It is worth restating that across all country groupings, 90% of the respondents admitted to being influenced to some degree because they liked chemistry at school, whereas 60% of the respondents outside of Vietnam were not influenced at all by their chemistry teachers. This suggests that educational and professional institutions should work together with chemistry teachers to raise the profile of the chemical engineering profession in the secondary school chemistry classroom. At the same time, careers teachers have little influence on students selecting chemical engineering. Further work, possibly including the use of focus groups, needs to be done to identify the reasons for this. It may be that there exists considerable scope for working with careers teachers to promote the profession.

By its very nature, this limited survey cannot gauge the effects that localized programs and activities such as those run by North Carolina State and Tufts have had on increasing interest in the profession. Nonetheless, this survey provides the basis of an international benchmark for comparing factors that influence students to select our profession for their future.

This survey has identified and to some extent quantified the important influences that acted on students currently enrolled in undergraduate chemical engineering degree programs. This work could be extended by surveying not only students before they have finally selected their courses, but also students currently enrolled in other engineering disciplines. The survey could also be extended to more non-English speaking countries.

The author welcomes contact from academics who might be interested in participating in another, more comprehensive survey.

ACKNOWLEDGMENTS

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Thanks to some excellent research in recent decades, we know a great deal about how learning happens and how little of it happens in lectures. As fascinated as professors think students should be with an hour of material like

\[
dA = -PdV - SdT \rightarrow dA = (\partial A/\partial V)_T dV + (\partial A/\partial T)_V dV \&
\]

\[
dG = VdP - SdT \rightarrow dG = (\partial G/\partial P)_T dP + (\partial G/\partial T)_V dV
\]

\[
& dH = (\partial H/\partial S)_T dS + (\partial H/\partial V)_T dV \rightarrow V = (\partial H/\partial P)_T = (\partial G/\partial P)_T \& (\partial P/\partial T)_S = (\partial S/\partial T)_P
\]

there's no mistaking the dazed stupor that falls over classrooms after even just a few minutes of it. Numbed minds can't learn. The students who decide that their interests lie in cutting that 8 a.m. class and getting more sleep may be right on target.

You have roughly 40 contact hours in a typical course. If all you do in them is lecture, you might as well just hand out your notes and let the students find something more productive to do with all that time. The only way a skill is developed—skiing, cooking, writing, critical thinking, or solving thermodynamics problems—is practice: trying something, seeing how well or poorly it works, reflecting on how to do it differently, then trying it again and seeing if it works better. Why not help students develop some skills during those contact hours by giving them some practice in the tasks they'll later be asked to perform on assignments and tests?

Which is to say, why not use active learning? At several points during the class,

1. Give the students something to do (answer a question, sketch a flow chart or diagram or plot, outline a problem solution, solve all or part of a problem, carry out all or part of a formula derivation, predict a system response, interpret an observation or an experimental result, critique a design, troubleshoot, brainstorm, come up with a question,...).

2. Tell them to work individually, in pairs, or in groups of three or four; tell them how long they'll have (anywhere from 10 seconds to two minutes); and turn them loose.

3. Stop them after the allotted time, call on a few individuals for responses, ask for additional volunteered responses, provide your own response if necessary, and continue teaching.

You may also occasionally do a think-pair-share, in which the students work on something individually and then pair up to compare and improve their responses before you call on them.

As little as five minutes of that sort of thing in a 50-minute class session can produce a major boost in learning. For starters, it wakes students up: we have seen some of them elbowing their sleeping neighbors when an active learning task was assigned. Academically weak students get the benefit of being tutored by stronger classmates, and stronger students get the deep understanding that comes from teaching something to someone else. Students who successfully complete a task own the knowledge in a way they never would from just watching a lecturer do it. Students who are not successful are

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The number of possible active learning tasks is limitless. At a minimum, you can ask the same questions you would normally ask in your lectures, only now you’ll get the whole class trying to answer them and not just the same two students who always answer them. You can also use any of the activities suggested in Item 1 of the list several paragraphs back, and you might occasionally run a TAPPS (“thinking-aloud pair problem solving”) exercise, arguably the most powerful classroom instructional technique for promoting understanding. Have the students work in pairs through a complex derivation or worked-out problem solution in the text or on a handout, with one of them explaining the solution step-by-step and the other questioning anything unclear and giving hints when necessary. Periodically stop them, call on several of them for explanations, provide your own when necessary, and have the students reverse roles in their pairs and proceed from a common starting point. It may take most or all of a class period to work through the entire solution, but the students will end with a depth of understanding they would be unlikely to get any other way.

Here are several techniques to make active learning as effective as possible.

• **At the beginning of the course, announce that you’ll be assigning short exercises during class and explain why you’re doing it (research shows students learn by doing, and the exercises will give them a head start on the homework and tests).** The explanation can help defuse the resistance some students feel toward any teaching approach other than the instructor telling them just what they need to know for the exam.

• **After an active learning exercise, call on a few individuals for responses before opening the floor to volunteers.** The knowledge that you might call on them gets active participation from students who would normally just sit passively and let others do the work.

• **Go for variety.** Vary the type of activity (answering questions, solving problems, brainstorming, etc.), the activity duration (10 seconds–2 minutes), the interval between activities (1–15 minutes), and the size of the groups (1–4 students). Mixing things up keeps active learning from becoming as stale as straight lecturing.

As many as half of the participants in our recent teaching workshops report using active learning in their classes, but nonusers often have concerns about the approach. (1) If I use active learning, will I still be able to cover my syllabus? (2) Can I do it in a really large class? (3) What should I do if some of my students refuse to participate?

We have offered detailed answers to the first two questions in another column and so will just give the short versions here. (1) Yes. (See Reference 4 for details on how.) (2) Yes, and in fact, the larger the class, the more important it is to use active learning. Try finding another way to get students actively engaged when there are 150 of them in the room.

What about students who refuse to participate? There may indeed be several who just sit staring straight ahead when groupwork is assigned, even after the awkwardness of the first few times has passed. We never see more than two or three of them in our classes, but for the sake of discussion let’s say it’s as many as 10% in yours. That means that while you’re doing an active learning exercise, 90% of the students are actively engaged with the material and getting practice in the skills you’re trying to teach them, and 10% are out to lunch. On the other hand, at any given moment in a traditional lecture, if as many as 10% of your students are actively involved with the lecture material you’re doing very well. No instructional technique works for all students at all times: the best you can do is reach as many as possible, and 90% is more than 10%. If some students opt out, don’t let it bother you—it’s their loss, not yours.

In short, if you start using active learning in your classes, you can expect to see some initial hesitation among the students followed by a rapidly increasing comfort level, much higher levels of energy and participation, and above all, greater learning. Check it out.

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All of the Random Thoughts columns are now available on the World Wide Web at 
http://www.ncsu.edu/effective_teaching and at http://che.ufl.edu/~cee/
FUTURE DIRECTIONS IN CHE EDUCATION
A New Path to Glory

This is the 2003 ConocoPhillips Lecture, presented at Oklahoma State University, Stillwater, Oklahoma, on April 25, 2003.

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The chemical engineering profession is in the midst of great change. Chemical engineers used to focus on making large quantities of small, relatively simple molecules (commodity products). With increasing frequency, in the future they will have to make smaller quantities of more complex, possibly biologically active, molecules and nanostructured materials (specialty products). Further, we used to only scale things up; now we must also scale down, as in lab-on-a-chip devices and portable fuel cells. In addition, developments in science and other engineering disciplines—such as nanoscale synthesis and characterization techniques, molecular biology and information technology—influence progress in our field. There is also a continuing need to consider what will be the energy sources for the future—conventional fuels such as oil, gas, and coal, or others such as nuclear, biomass, and solar? Finally, growing environmental considerations in society make us aware of the long-term and global implications of our manufacturing practices.

I would like to discuss how all these factors, currently at play, will impact the education of chemical engineers primarily at the undergraduate level, although some remarks will also be made toward graduate education and research opportunities.

THE DEVELOPMENT OF CHEMICAL ENGINEERING

Before turning toward the future, it is instructive to first examine how the discipline of chemical engineering evolved. Fascinating detailed accounts of early developments in the curriculum and the profession have been presented in many sources,\(^6\) so I will keep this discussion brief.

It is generally agreed that chemical engineering as a distinct discipline began in January of 1888 when George E. Davis gave a series of twelve lectures on the subject at the Manchester Technical School in England. He had previously coined the term “chemical engineer” in 1880 and promoted it (unsuccessfully) to found a society of chemical engineers. The first four-year undergraduate chemical engineering degree program was established at MIT by the chemistry professor Lewis Mills Norton in 1888. It was soon followed by those at the University of Pennsylvania (1892), Tulane (1894), Michigan (1898), and others, including our own at Notre Dame (1909). Most early curricula had their origin in chemistry departments, although there are examples of some evolving from mechanical (e.g., Colorado, 1904) and electrical (e.g., Wisconsin, 1905) engineering departments as well.

The early chemical engineering curricula included an amalgam of courses taken by chemists and mechanical engineers, with those in industrial and applied chemistry in the third and fourth years being unique to the field. The discipline received its first unifying theme with development of the concept of “unit operations,” which is often called the first paradigm of chemical engineering. It grew out of the realization that purely physical operations of chemical processing, whether to produce smaller quantities of fine or larger amounts of heavy chemicals, all depended on certain common principles of physics and chemistry. As first noted by Arthur D. Little (1915) in the Chemical Engineering Visiting Commit-
The discipline received its first unifying theme with development of the concept of "unit operations," which is often called the first paradigm of chemical engineering.

principles of momentum, mass, and heat transfer, it is possible to understand the unit operations. It was an extremely influential textbook that charted the education, development, and practice of chemical engineering for decades.

The first significant textbook for the discipline, Principles of Chemical Engineering by Walker, Lewis, and McAdams of MIT, appeared in 1923. It showed that by combining a few principles of momentum, mass, and heat transfer, it is possible to understand the unit operations. It was an extremely influential textbook that charted the education, development, and practice of chemical engineering for decades.

Soon after the introduction of unit operations, attention turned to developing procedures for overall material and energy balances in processes, including single or multiple reactions, recycle, and bypass, and curricula in the 1930s included courses in industrial chemical calculations. In the 1940s, courses in thermodynamics were introduced that included properties of gases and liquids and applications of both the first and second laws. This decade also saw the development of courses in equipment and process design.

Although there were important efforts in German, notably by Damköhler, the systematic development of chemical and catalytic reaction engineering principles in the English language, using information on reaction rates and catalysis, waited until the appearance in 1947 of Chemical Process Principles: Part III. Kinetics and Catalysis by Hougen and Watson. By the end of the 1950s, most chemical engineering undergraduates took formal courses in reaction engineering and courses in process control were initiated.

All through this period, since the early days of the profession, a synergistic relationship existed between academia and industry. Much of university research was supported by industry, and the graduates were readily employed by the growing petroleum refining, petrochemical, and chemical industries. The oil companies refined petroleum crude to produce gasoline and other fuels for automobiles and airplanes, the petrochemical complexes produced bulk chemicals, while the chemical companies produced these as well as polymers, fertilizers, paints, and other specialty chemicals. All these products satisfied a rising demand from a society that had an increasing standard of living. The growth of the petroleum and chemical industries followed, and in turn catalyzed, developments in chemical engineering.

The 1950s also saw a greater emphasis on the use of analysis and applied mathematics in solving chemical engineering problems that can be traced to three separate events. First, it was recognized that the individual unit operations involve a combination of the same basic principles in microscopic momentum, heat, and mass transport, each with similar mathematical descriptions. Thus, a study of the individual transport processes as a unified subject "Transport Phenomena" can lead to a greater understanding of chemical processes; this concept was greatly aided by the appearance of a famous book in 1960 with that same title, written by Bird, Stewart, and Lightfoot. Second, applications of sophisticated mathematical techniques were yielding strong results for the design and operation of separation processes and chemical reactors, as exemplified in the works of Amundson. Finally, the general availability of computers, whereby it became possible to conduct numerical simulations of process models to identify optimal design and operating conditions, also accelerated the application of analytical and numerical techniques.

Thus, the 1950s and 60s saw the emergence of the so-called engineering science approach in the discipline—the second paradigm in chemical engineering. This approach led to a curriculum at both the undergraduate and graduate levels that is a unique blend of chemistry, physics, and mathematics. The chemical engineers educated in this manner could effectively develop, design, and operate complex chemical processes that typically produced commodity products.

CURRENT STATUS AND CHALLENGES

I will now examine the current status of the discipline as it relates to the education and employment of chemical engineers. I will be brief since the topic has been addressed well in a lecture by Ed Cussler last year and elsewhere. Further, there is much discussion of these issues in the context of undergraduate curriculum revitalization as a result of the "New Frontiers in ChE Education" workshops organized through the Council for Chemical Research (CCR) and sponsored by the National Science Foundation (NSF).

Education

A typical undergraduate chemical engineering curriculum consists of foundation courses in mathematics, physics, chem-
istry, and engineering in the early years, as well as courses in humanities and social sciences that serve to provide a broad education. The chemical engineering courses typically include offerings in mass and energy balances, thermodynamics, transport processes, separations, reaction engineering, process design, process control, and laboratories where principles learned in the lecture courses are reinforced and include elements of both written and oral communication of experimental results and analysis. Finally, there are generally several electives to choose from, in chemical engineering as well as in other science and engineering disciplines.

A striking fact is that while the discipline of chemical engineering has evolved significantly over the last forty or so years (as I shall detail next), the undergraduate curriculum has remained essentially unchanged. The engineering science paradigm continues to dominate the core curriculum as well as the textbooks that are used. The examples used in courses continue to come primarily from the petroleum refining and bulk chemicals production industries.

**Employment**

Between 50% and 60% of the BS degree chemical engineering graduates in the U.S. seek industrial employment immediately upon graduation—Figure 1 shows their distribution during the 2000-01 year by nature of the industry. It is remarkable that the skills learned from understanding engineering principles and processes, based largely on physical and chemical transformations, are considered to be valuable by a large number of industries. If we consider chemical and energy companies as the traditional employers, however, then only about 40% of chemical engineers find their initial employment there. About an equal number go to the electronic, food/consumer products, biotechnology, and materials-related industries, which were not significant employers some years ago. Overall, as noted elsewhere, only about 25% of the graduates are hired by companies that manufacture commodity chemicals emphasized in the curriculum, while about 50% go to those with a product orientation—in contrast with approximately 80% and 15%, respectively, twenty-five years ago.

In addition to the increasingly wider spectrum of industries where chemical engineers now find employment, several other factors currently at play, even with the traditional energy and chemical companies, are:

- The companies are becoming more global, with a greater fraction of their manufacturing and research conducted overseas
- Many companies are merging into larger ones, with significant reductions in the workforce
- Chemical companies are increasingly incorporating life sciences into their manufacturing and products
- Chemical engineers cannot expect to work with a single company or industry type and must now accept several job changes over their professional careers

**Other Driving forces**

There are also other driving forces currently operative, and I would like to enumerate some of them, without claiming completeness. First, biology is rapidly developing as a molecular-based science so that its connections can now be made more readily to chemical engineering. There are numerous opportunities for coupling molecular-level understanding of biological reactions and interactions with chemical engineering concepts and processes, that can result in products of tre-
mendous value. Some examples are bioprocessing for production of pharmaceuticals and even commodity chemicals, metabolic engineering, controlled drug delivery, biomaterials, tissue engineering, functional genomics, gene therapy, drug design and discovery, nano and micro biotechnology for lab-on-a-chip devices, etc.

Second, there is a current trend toward establishment of bioengineering and biomedical engineering departments, driven by the Whitaker Foundation grants (see, for example, Ref. 16). Owing to the closest fit, these new programs compete for students and resources that in many instances would otherwise come to chemical engineering.

Third, there is growing awareness of the pressures that current manufacturing practices place on the environment in terms of pollutants that require remediation and waste generation that demands disposal and diminishes resource utilization. Thus, environmentally benign processing and sustainable development is receiving increased attention, both to satisfy environmental regulations and to increase profitability.

Fourth, new educational tools and methods are being developed that can be used to enhance the quality of chemical engineering education. Examples include use of web-based educational materials that can be shared across institutions, web interfaces to run actual laboratory experiments, and simulations to explore influence of parameters or to learn about cases too dangerous to conduct in the laboratory, such as explosions.

THE FUTURE DIRECTIONS

Based on the current status of the discipline, some suggestions can now be made for future directions of chemical engineering education, especially at the undergraduate level. The intent is to provide a framework that takes advantage of both the unique aspects of the present curriculum and the changing scene related to employment and developments in other science and engineering disciplines. My basic premise is that the defining characteristics of chemical engineers, i.e., the ability to apply molecular level understanding to convert raw materials into more valuable products by physical, chemical and biological transformation using economic and safe processes, should remain unaltered. Thus, the core subjects in the curriculum involving mass and energy balances, thermodynamics, transport processes, reaction engineering, separations, laboratories, and design should continue in the future, but with structural modifications as discussed below.

Expanded Examples of Applications

As noted earlier, chemical engineers now find employment in a wide variety of industries. It is apparent that their skill set, which includes chemistry in addition to physics and mathematics also available to other engineering disciplines, makes them uniquely qualified to impact a diverse set of technologies. The curriculum, however, continues to include examples primarily from the petroleum refining, petrochemical, and bulk chemicals industries. It is important to broaden the scope by including examples from areas such as materials processing, biotechnology, pharmaceuticals, food processing, and environment. Similarly, when discussing design, considerations of product and not merely process should be included. These movements will require new textbooks and teaching modules. Some steps in this direction are already being taken.

Modern Biology as an Underlying Fundamental Science

Recent developments in molecular and cellular biology, the similarity of using biological and chemical reactions at the molecular level for design of new products and processes, and the growth of biotechnology industries where chemical engineers are currently employed (and from all indications will be in greater numbers in the future) all suggest that biology will soon reach an almost equal status with chemistry as a basic science in defining chemical engineering. Thus, it is now timely to include one or two formal courses in biology and biochemistry in the early years of the undergraduate curriculum. This requires two types of actions: one, working together with the relevant disciplines to arrive at suitable courses, and two, incorporating elements of biology within all the chemical engineering courses just as chemistry is today. Thus, for example, in the reaction engineering course, building upon knowledge of biochemistry and biology gained earlier, connections between molecular mechanisms and macroscopic kinetics could be made and related to modeling of cells and bioreactors, similar to what is done today with chemical catalysis and diffusion-reaction in catalyst pellets leading to fixed-bed reactor design. Similarly, based on biological understanding, separations courses can readily include living systems and processing of biomolecules.

Numerous opportunities also exist in other core courses, such as mass and energy balances, thermodynamics, transport processes, and design. These developments are likely to take some time to materialize, but movement in this direction is critical for chemical engineers to contribute effectively and exercise leadership in the biotechnology areas that offer tremendous potential for growth.

Fall 2003
Recruitment of Talented and Motivated Students

People are our greatest asset, so for the vitality and future of the discipline we must attract the best and the brightest to chemical engineering. This will occur naturally if we offer imaginative courses and programs involving new technologies, use newer methods and tools in our teaching, and provide intellectual challenges for our students, so that they have promise of a bright future while solving important problems facing society.

A specific method I have found to be effective in challenging students intellectually is to involve them in undergraduate research. The opportunity to do an independent project with only general overall guidelines provided, often using equipment assembled on their own, is stimulating for most students. Over the last ten years, when I began to keep a record of this activity, 25 undergraduates have conducted research in my laboratory, many starting in their junior year, and some 15 have gone on to attend graduate school elsewhere, most for PhD degrees. (In a lighthearty vein, I sometimes say that I have saved a large number of brilliant chemical engineers from leaving our profession for careers such as in medicine or law—of course, I do not say this in front of my daughters, one a lawyer and the other studying to become one!) Many work closely with a graduate student or a postdoctoral associate, to mutual benefit, and I have a number of journal papers with undergraduates as coauthors. Undergraduate research exposes students to the frontiers of the field and provides the intellectual challenges that are difficult to match in typical lecture or laboratory courses.

Name Change of Departments

As noted earlier, the chemical engineering profession is changing rapidly and faces many new challenges. The most impressive movement appears to be the emergence of modern biology as a fundamental science, on an almost equal footing with chemistry, in defining the field. Further, all indications are that its role will continue to grow in the future. For this and other pragmatic reasons, including the facts that students are attracted to biological departments and degree names and that we face new competition for students and resources from new bioengineering and biomedical engineering departments (some 90 such departments already existed at the end of 2001[15]), many chemical engineering departments are changing their names to include some biological term. Among several that are possible, chemical and biomolecular engineering seems to be gaining acceptance, as adopted recently by departments at Cornell, Illinois, and ours at Notre Dame. It connects with the scientific base of the discipline, is more inclusive of modern biotechnology as compared with alternatives, and owing to its molecular focus, it offers more potential for collaborations with biochemists and biologists. Thus, while William Shakespeare’s Juliet asks, “What’s in a name? That which we call a rose, by any other name would smell as sweet,” for the reasons cited, I favor departmental name changes.

Graduate Education and Research

Although I have limited my remarks so far to undergraduate education, I would like to say a few words about graduate education and research. Graduate education also started in the early 1900s, at both the MS and PhD levels. The core graduate curriculum has essentially mirrored the curriculum at the undergraduate level, with the former always being more fundamental and mathematical in content. Thus, courses in thermodynamics, kinetics and reaction engineering, transport processes, and mathematical analysis, based on the engineering science approach, are currently required in most graduate programs. They are augmented by other courses in chemical engineering, various sciences, and other engineering disciplines, to suit the student’s research needs and interests. Similar to the undergraduate courses, the graduate courses also need to include examples in newer application areas and incorporation of biology, particularly as it is introduced in the earlier years.

In research, chemical engineering graduate programs have moved forward rapidly to embrace all areas of new technologies, including biological, materials, environmental, information, and energy. This movement was promoted by the National Research Council’s “Frontiers in Chemical Engineering” report published in 1988,[17] whose recommendations were recently reinforced and updated.[18] Further, there is a growing trend toward interdisciplinary research involving faculty members and students from different fields working together to solve research problems. This trend has its origin in at least two related facts: one, the cutting-edge prob-
By offering imaginative courses that use new teaching methods and tools, and by providing intellectual challenges, we will be able to attract the best and brightest to chemical engineering and educate them to become leaders in industry, academia, and society.

Problems are often at the interface between disciplines, and two, funding agencies (now primarily federal and state, as compared to mainly industrial prior to the 1950s) seem to favor this approach. In turn, universities have responded by establishing research centers, typically involving colleges of science and engineering but sometimes also business or public policy, that facilitate interdisciplinary interactions. While the coexistence of traditional departments and centers can lead to tension, I believe that organization along these lines is required and that this structure is here to stay for some time.

Finally, there is another movement currently occurring in the chemical engineering discipline, particularly at the graduate education and research levels. On one hand, in addition to a molecular-level description of chemical and biological transformations and processes, there is growing feasibility now to also conduct molecular-scale simulations to compute thermodynamic, transport, and other properties of fluids and materials. On the other hand, owing to the strengths of analysis inherent in the engineering science approach, along with a systems view, it is possible to analyze complex systems and their interactions. These directions are changing the nature of chemical engineering such that it could be claimed that molecular engineering of products and processes is emerging as a new paradigm for the discipline. This movement will take some time to significantly influence the education of chemical engineers at the undergraduate level, and there is current discussion ongoing in this regard.

CONCLUDING REMARKS

Chemical engineering as a distinct discipline started with applications primarily in petroleum refining and bulk chemicals production industries, but skills developed as a result of a solid foundation in the fundamental sciences (chemistry, physics, mathematics, and now increasingly, biology), along with a quantitative engineering science approach, have permitted chemical engineers to move rapidly into many of the emerging technologies. Their impact in the newer areas will be enhanced by continuing the core curriculum and augmenting it by expanding examples of applications, incorporating biology in all core courses, and including orientation toward both product and process design. By offering imaginative courses that use new teaching methods and tools, and by providing intellectual challenges, we need to attract the best and brightest to chemical engineering and educate them to become leaders in industry, academia, and society.

I hope that these remarks, along with the current discussion ongoing in the NSF/CCR workshops, will lead to innovative chemical engineering programs that involve new technologies and provide a bright future for our students while solving important problems facing society.

ACKNOWLEDGMENTS

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EXCEPTIONS TO THE LE CHATELIER PRINCIPLE

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When studying chemical reactions within a single phase, chemical engineers require knowledge of the equilibrium constants. For a given temperature and pressure, equilibrium compositions may then be calculated for all relevant reactions. If the temperature, pressure, or composition of one of the components changes, however, the equilibrium position usually shifts. The direction of such shifts can be calculated by direct computation of the new equilibrium state.

Observations of the direction of shifts in the equilibrium position led to the formulation of a general statement referred to as the “Principle of Le Chatelier,”[1] or sometimes as the “Principle of Le Chatelier and Braun.”[2] Le Chatelier’s principle can be stated as follows:[1]

In a system at equilibrium, a change in one of the variables that determines the equilibrium will shift the equilibrium in the direction counteracting the change in that variable.

The above statement is useful in inferring, without direct calculation, the effects of changes in a system initially at equilibrium. Yet, still not widely known, particularly in the chemical engineering literature, is that Le Chatelier’s principle is not universally valid, and exceptions are known to occur. (See, however, Sandler[2] and Tester and Modell[3] as examples of current chemical engineering textbooks that highlight the limitations of the above statements. Exceptions to Le Chatelier’s principle appear to be more widely known in the physical chemistry literature and have been discussed for some time. See, for example, de Heer[4] and Liu, et al.[5] for an historical account of Le Chatelier’s principle.)

Consider, for example, the ammonia synthesis reaction

\[ \text{N}_2 + 3\text{H}_2 \rightleftharpoons 2\text{NH}_3 \]

in which equilibrium has been established at a given temperature, T, and pressure, P. Le Chatelier’s principle predicts that the reaction will shift to the right (i.e., more ammonia will be produced) upon the addition of more nitrogen to the reaction vessel. If the initial mole fraction of nitrogen exceeds 0.5 and the given T and P are held fixed, however, the reaction instead proceeds to the left, producing more nitrogen, as predicted from rigorous equilibrium constant calculations (the value of 0.5, as shown later, is calculated assuming ideal gas behavior). This shift to the left is a clear exception to the principle of Le Chatelier, which has not been rigorously proven[4]

Proofs of this unexpected shift have been given before.[4,6] Most chemical engineering texts do not provide a proof, except, for example, Tester and Modell,[3] which does provide a detailed proof. The most widely referenced and reproduced proof is by Katz[6] (the procedure followed in Liu, et al.,[5] is nearly the same as the approach by Katz, although the au-
To address the technical and educational issues of Le Chatelier’s principle, we therefore present in this paper a new and conceptually more straightforward analysis of the direction of the equilibrium shift for the ammonia synthesis reaction as an example.

The use of a reaction quotient can be confusing to students, particularly to students exposed to reaction equilibria for the first time. To address the technical and educational issues of Le Chatelier’s principle, we therefore present in this paper a new and conceptually more straightforward analysis of the direction of the equilibrium shift for the ammonia synthesis reaction as an example. Our approach is, however, more general. In contrast to the other methods, changes at constant T and P are now considered in which the value of the reaction quotient is strictly held fixed and equal to the equilibrium constant. Hence, the analysis makes no use of a separately defined reaction quotient (that is applicable whether equilibrium is or is not established) and should be easier for students to understand. The analysis also involves finite, as well as infinitesimal, changes, which can be the basis of future experimental tests that may demonstrate more vividly the key thermodynamic laws (see del Pino, et al.,17 for an example of a simple experiment concerning shifts of chemical equilibrium).

Le Chatelier's principle can be reformulated in a more general way that becomes universally valid,14,51 although it bears little resemblance to the statement given earlier. For pedagogical reasons, we briefly discuss this new general statement in the last section of this paper. An excellent overview, and proof, of this new general statement is given by de Heer.41 It is, however, only valid for infinitesimal changes from the initial equilibrium state.51 In this paper, we also consider the ammonia synthesis reaction for the case of adding nitrogen in finite amounts (Liu, et al.,51 considered finite additions as well, but the present analysis provides a more straightforward and quantitative discussion). The value of 0.5 for the mole fraction of nitrogen, above which the reaction proceeds to the left while below the reaction proceeds to the right, is shown to be true for infinitesimal additions of nitrogen.

For finite changes, no universally valid statement on the direction in which the reaction shifts can be formulated, and thus each case must be considered individually. In such cases, instructors should advise ignoring the reformulated Le Chatelier’s principle and instead should calculate, in general, the shift in the equilibrium state directly from the relations of chemical equilibrium.

**AMMONIA SYNTHESIS REACTION**

**Exception to the Principle of Le Chatelier**

Let us consider the ammonia synthesis reaction and assume for simplicity that the components comprise an ideal-gas mixture. Analyses for nonideal mixtures, although possible, have not been reported. Let species 1 represent nitrogen, species 2 hydrogen, and species 3 ammonia. The chemical potential of each species i, \( \mu_i \), in the ideal-gas mixture is given by8

\[
\mu_i = \Gamma_i(T) + RT \ln y_i P
\]

where \( \Gamma_i(T) \) is the chemical potential of pure component i, as an ideal gas, at the temperature T (and a fixed reference pressure \( P_0 \)). \( R \) is the ideal gas constant, \( P \) is the system pressure, and \( y_i \) is the mole fraction of species i. At equilibrium, the chemical potentials of the components participating in the chemical reaction must satisfy8

\[
\sum y_i \mu_i = 0
\]

Next, let the system be at equilibrium at a given T and P. At the initial equilibrium state, there are \( n_1^0 \), \( n_2^0 \), and \( n_3^0 \) moles of each species with mole fractions \( y_1^0, y_2^0, \) and \( y_3^0 \) satisfying Eq. (3). Next, we consider the addition of \( \Delta \) moles of nitrogen (1), while keeping T and P constant. As the system re-equilibrates, the reaction proceeds so that the final mole numbers of each species will be given by8

\[
\begin{align*}
    n_1 &= n_1^0 + \Delta - \xi \\
n_2 &= n_2^0 - 3\xi \\
n_3 &= n_3^0 + 2\xi
\end{align*}
\]
where $\xi$ is the extent of reaction starting from the above initial equilibrium state; $\xi$ is defined to be positive if the reaction proceeds to the right, i.e., nitrogen and hydrogen are consumed while ammonia is produced, and negative if the reaction proceeds to the left. The above relations imply that the final mole fractions are given by

\[
y_1 = \frac{n_0^0 + \Delta - \xi}{n_0 + \Delta - 2\xi}, \quad y_2 = \frac{y_0^0 - 3\xi}{1 + \Delta' - 2\xi}, \quad y_3 = \frac{y_0^0 + 2\xi}{1 + \Delta' - 2\xi}.
\]

(5)

where $n = n_0^0 + n_0^2 + n_0^3$, $\Delta' = \Delta / n_0$, and $\xi'$ = $\xi / n_0$; $\Delta'$ and $\xi'$ are dimensionless quantities. Since $T$ and $P$ are held constant, Eq. (3) implies that

\[
\left( y_3 + 2\xi' \right)^2 \left( 1 + \Delta' - 2\xi' \right)^2 = K_p(T,P) = \left( y_0^0 \right)^2 \left( y_2 \right)^3
\]

(6)

Equation 6 is valid for all values of $\Delta'$ and can be used to determine the value of $\xi'$ for a given choice of $\Delta'$. The sign of $\xi'$, however, determines the direction in which the reaction shifts, and its value determines the extent of the reaction triggered by the addition of nitrogen.

First, we focus on how the extent of the reaction varies when an infinitesimal amount of nitrogen, i.e., $\Delta' \to 0$, is added. One can solve Eq. (6) for various values of $\Delta'$ and then determine the sign of $\xi'$ as $\Delta' \to 0$. But since $\xi' \to 0$ as $\Delta' \to 0$, we instead determine $d\xi' / d\Delta'$ analytically for $\Delta' \to 0$. To proceed, and for ease of further manipulations, we first rewrite Eq. (6) as

\[
\left( y_3^0 + 2\xi' \right)^2 \left( 1 + \Delta' - 2\xi' \right)^2 = K_p(T,P) = \left( y_0^0 \right)^2 \left( y_2 \right)^3
\]

(7)

We now differentiate both sides of Eq. (7) with respect to $\Delta'$ for constant $y_0^0, y_2^0, \text{ and } y_3^0$, letting $\eta = d\xi' / d\Delta' = d\xi / d\Delta$. We then take the limit for $\Delta' \to 0$, with $\xi' \to 0$ as well, and finally solve for $\eta$. After a few lines of algebra, we obtain

\[
\eta = \frac{d\xi'}{d\Delta} = \frac{y_3^0 y_2^0 \left( 1 - 2y_0^0 \right)}{4y_1^0 y_2^0 \left( 1 - y_0^0 \right) + y_2^0 y_3^0 + 9y_1^0 y_0^0}.
\]

(8)

Since the denominator in Eq. (8) is always positive, the sign of $\eta$ is given by the sign of $(1 - 2y_0^0)$. Therefore, for infinitesimal additions of nitrogen, we conclude that

\[
y_1^0 < \frac{1}{2}, \quad \eta > 0: \quad \text{reaction proceeds to the right, against the Le Chatelier Principle}
\]

(9a)

\[
y_1^0 > \frac{1}{2}, \quad \eta < 0: \quad \text{reaction proceeds to the left, against the Le Chatelier Principle}
\]

(9b)

\[
y_1^0 = \frac{1}{2}, \quad \eta = 0: \quad \text{no reaction takes place, against the Le Chatelier Principle}
\]

(9c)

Hence, the exception to Le Chatelier’s principle occurs when the initial equilibrium mole fraction of nitrogen is equal to or exceeds 0.5 and is independent of the mole fractions of the other species or of the values of the temperature and pressure.

Why the reaction reverses direction can be understood qualitatively[11 by considering the form of the reaction quotient in Eq. (3). The addition of nitrogen increases the mole fraction of nitrogen, $y_1$, but also causes a decrease in $y_2$ (hydrogen) and $y_3$ (ammonia). Since $y_2$ is cubed in the denominator of the reaction quotient, the decrease in $y_2$ may have a more significant effect on the reaction quotient than the increase in $y_1$ or decrease in $y_3$. When the mole fraction of nitrogen is small, the change in $y_1$ upon addition of some nitrogen yields a proportionally larger change in $y_1$ than the decreases in $y_2$ and $y_3$. To compensate, and so ensuring that the reaction quotient must remain equal to $K_p(T,P)$, the reaction proceeds to the right, reducing some of the added nitrogen and producing more ammonia. When the mole fraction of nitrogen is large, so that the mole fraction of hydrogen is small, the proportional decrease in $y_2$ is greater than the increase in $y_1$. The decrease in $y_2$ is magnified by the appearance of $y_1$, and so the reaction proceeds to the left, generating more nitrogen and

![Figure 1. Extent of reaction versus the amount of nitrogen added for $y_1^0 = 0.5$.](image-url)
hydrogen (thereby offsetting, to some degree, the decrease in $y_2$). Why the reaction shifts direction when $y_1$ exceeds 0.5 is, however, not readily apparent from the above analysis. The composition at which the reaction changes direction is, in general, dependent on the form of the reaction quotient.\[6\]
The above exceptions, relations (9b) and (9c), do not occur when hydrogen or ammonia are added to the system or when the temperature and volume are held constant.\[1,61\] The addition of an inert species does not alter the conclusions. Many other reactions can exhibit such exceptions to Le Chatelier’s principle, including liquid-phase reactions. Katz\[61\] considers in general the conditions under which a reaction with several reactants and products shifts to the left. The results depend on the stoichiometric coefficients of the given species and can be analyzed similarly as above. Such examples can provide useful teaching assignments, and use of nonideal gas models may provide further enrichment.

Equation (8) and the conclusions of (9) are valid only for infinitesimal additions of nitrogen at constant $T$ and $P$. Equation (6) or (7), however, is valid for finite additions of nitrogen at fixed $T$ and $P$. To determine how the reaction shifts upon addition of a finite amount of nitrogen, one must use Eq. (6) or (7) to determine the value (and sign) of $\xi'$ for a given value of $\Delta'$. Given that $y_i^o = 1 - y_i^{\infty} - y_z^o$, Eq. (7) can be rewritten as

$$\left(1 - y_1^o - y_2^o + 2 \xi' \right) \left(1 + \Delta' - 2 \xi' \right) y_1^o (y_2^o)^3 = \left(1 - y_1^o - y_2^o \right) \left( y_1^o + \Delta' - \xi' \right) \left( y_2^o - 3 \xi' \right)^3 \quad (10)$$

This equation is fourth-order in $\xi'$ with roots that depend on $\Delta'$, $y_1^o$, and $y_2^o$. The physically relevant value of $\xi'$ must be such that each of the terms in parentheses in Eq. (10) and the final mole fractions of Eq. (5) lie between 0 and 1. For small to moderate values of $\Delta'$, the physically relevant solution of Eq. (10) is therefore small. Equation (10) was solved by the standard Newton-Raphson’s method with an initial guess of $\xi' = 0$. Convergence to the one physical root was readily achieved. Values of $\xi'$ were generated for a range of $\Delta'$ at a given $y_1^o$ and $y_2^o$. One may vary $y_2^o$ independently from $y_1^o$, with the constraint that $0 < y_2^o < 1 - y_1^o$. Equation (10), like Eqs. (6) and (7), also does not require that one specify the pressure and temperature explicitly. The value of $y_2^o$ for a given $y_1^o$ must be consistent with the choice of $T$ and $P$ in Eq. (3), but the specific value of $T$ and $P$ is not required for the determination of $\xi'$.

Figure 1 displays a plot of $\xi'$ versus $\Delta'$ for $y_1^o = 0.5$ and different values of $y_2^o$. In all cases, $\xi' \rightarrow 0$ as $\Delta' \rightarrow 0$, and the slope of $\xi'$ approaches zero as $\Delta' \rightarrow 0$, consistent with relation (9c). Nonetheless, for any finite addition of nitrogen, the reaction proceeds to the left, i.e., $\xi' < 0$. The value of $\xi'$ is quite small, remaining so as $\Delta' \rightarrow 1$. The reaction proceeds to the left, but only by a relatively small extent, even if nitrogen is added in an amount equal to the total number of moles of all the species initially present (e.g., $\xi' = -0.006$ for $\Delta' = 1.0$ and $y_2^o = 0.30$). The extent of reaction, though always negative, also depends on $y_2^o$.

Figures 2 and 3 display plots of $\xi'$ versus $\Delta'$ for $y_1^o = 0.7$ and $y_1^o = 0.25$, respectively, at different values of $y_2^o$. When $y_1^o = 0.7$, the limiting slopes are all negative, consistent with relation (9b), and a finite addition of nitrogen, at least up to $\Delta' = 1$, causes the reaction to proceed to the left ($\xi' < 0$). When $y_1^o = 0.25$, the limiting slopes are all positive, again as required by relation (9a), and a finite addition of nitrogen up to $\Delta' = 1$ causes the reaction to proceed to the right ($\xi' > 0$). Yet, the curves in Figure 3 display maxima, suggesting that for suffi-
ciently large \( \Delta' \), the curves will eventually yield negative values of \( \xi' \).

To illustrate this effect further, we consider Figure 4 in which \( y_1^o = 0.45 \). As required by relation (9a), all the curves initially have a positive slope, so that the reaction proceeds to the right for small values of \( \Delta' \). At some critical value of \( \Delta' \) (which depends slightly on \( y_2^o \)), \( \xi' \) becomes negative. Therefore, at \( y_1^o = 0.45 \), the reaction proceeds to the right for small additions of nitrogen, but shifts to the left when a sufficient quantity of nitrogen is added. The figures suggest that for all values of \( y_1^o \), the reaction will eventually proceed to the left if a large enough amount of nitrogen is added to the reaction vessel. These calculations also suggest ways for experimentally testing the predictions and demonstrating the thermodynamic laws.

**GENERALIZATION OF LE CHATELIER'S PRINCIPLE**

**The Principle of Moderation**

We close this paper by briefly discussing the generalized statement of Le Chatelier as stated and proved by de Heer,[4] which is more appropriately called a Principle of Moderation (the proof given by de Heer is beyond the scope of an undergraduate course). Since generality often causes one to sacrifice simplicity, the more general principle of moderation may be given as[4]

The change of an intensive variable caused by changing the corresponding (conjugate) extensive variable is smaller if chemical equilibrium is maintained than if no reaction could take place in the system.

The change of an extensive variable caused by changing the corresponding (conjugate) intensive variable is larger if chemical equilibrium is maintained than if no reaction could take place in the system.

The above statement has been shown to be valid only for infinitesimal changes from the initial equilibrium state.[4,5] It does not necessarily hold for finite changes.[5]

The principle of moderation applies, for example, to the change of the chemical potential of nitrogen (intensive variable) upon the addition of nitrogen (conjugate extensive variable). With the ammonia synthesis reaction prevented from occurring, the addition of nitrogen at constant \( T \) and \( P \) yields an increase in the value of the chemical potential of nitrogen. If nitrogen were instead added while maintaining chemical equilibrium, i.e., the reaction was allowed to proceed, the resultant increase in the chemical potential of nitrogen would be smaller than the increase obtained when the reaction was prohibited. In other words, the change in the chemical potential of nitrogen is moderated, or lessened in this example, by the reaction.

Since at constant \( T \) and \( P \) the chemical potential of a component in an ideal-gas mixture increases with increasing mole fraction, we instead analyze the change in the mole fraction of nitrogen upon the addition of nitrogen to illustrate in more detail the principle of moderation (this is one aspect of the ammonia synthesis reaction that was not directly discussed by de Heer). We consider the addition of nitrogen with the ammonia synthesis reaction taking place and with the reaction prevented from occurring. From Eq. (5), we see that in the limit of \( \Delta' \to 0 \)

\[
\frac{dy_1}{d\Delta'} = 1 - y_1^o + \eta(2y_1^o - 1) \tag{11}
\]

If no reaction is allowed to take place, then the final mole fraction of \( y_1 \) is equal to

\[
y_1 = \frac{y_1^o + \Delta'}{1 + \Delta'} \tag{12}
\]

Taking the derivative of \( y_1 \) with respect to \( \Delta' \), we find in the limit of \( \Delta' \to 0 \) that

\[
\left( \frac{dy_1}{d\Delta'} \right)_{\text{no rxn}} = 1 - y_1^o > 0 \tag{13}
\]

Equations (11) and (13) imply that

\[
\frac{dy_1}{d\Delta'} = \left( \frac{dy_1}{d\Delta'} \right)_{\text{no rxn}} + \eta(2y_1^o - 1) \tag{14}
\]

Since Eq. (8) indicates that \( \eta(2y_1^o - 1) \leq 0 \), then

\[
\frac{dy_1}{d\Delta'} \leq \left( \frac{dy_1}{d\Delta'} \right)_{\text{no rxn}} \tag{15}
\]

The extent of reaction versus the amount of nitrogen added for \( y_1^o = 0.45 \) is depicted in Figure 4.
or the change in the mole fraction of nitrogen is always less (or equal) when the reaction proceeds than when no reaction takes place. The reaction is said to “moderate” the mole fraction of nitrogen, i.e., the reaction decreases the final mole fraction of nitrogen as compared to the case when no reaction occurs. This result is counter-intuitive, since Eq. (15) is also valid when the reaction shifts to the left, thereby producing more nitrogen. In this instance, the additional hydrogen that is produced by the reaction shifting to the left offsets the increase in the mole fraction of nitrogen.

Similar arguments, as discussed by de Heer, show that the partial pressure and chemical potential of nitrogen are also moderated by the reaction: the change in these intensive quantities is always less when the reaction occurs than when no reaction takes place. Equation (15) also supports these conclusions since, at constant T and P, the partial pressure and chemical potential of a component in an ideal gas mixture increase with increasing mole fraction.

For finite additions of nitrogen, and for most conditions, calculations show that Eq. (15) is still satisfied. There are ranges of finite $\Delta'$, however, in which the reaction does not moderate the change in mole fraction of nitrogen (a value of $y_{N2}^0 = 0.45$ provides an example for $\Delta'$ between approximately 0.12 and 0.22). In this case, the final mole fraction of nitrogen after reaction is in fact greater than the final mole fraction of nitrogen without reaction. The ratio of the final mole fraction of nitrogen with reaction to the mole fraction without reaction is, however, only slightly greater than unity. Thus, in this case, the violation of the principle is minor for finite values of $\Delta'$.

CONCLUSIONS

When a gas-phase system is at chemical reaction equilibrium at constant temperature and pressure, and some extra reactant or product is added, the system, upon reestablishing equilibrium does not always respond in a way qualitatively consistent with the traditional Le Chatelier principle. If there is a change in the number of moles, as in the ammonia synthesis reaction, then adding one reactant ($N_2$) may cause the reaction to proceed in a direction that produces more of the added ingredient ($N_2$). These results are perfectly consistent with the laws of thermodynamics. The direction of the reaction depends on whether the added amount is infinitesimal or finite. For infinitesimal additions, a new principle of moderation, first suggested formally by de Heer, does apply. Even this principle does not apply for finite additions of reactant ($N_2$). These results indicate that the principle of Le Chatelier should be taught in its more general form. In addition, instructors should emphasize that even the more general formulation is valid for infinitesimal changes only. (Nonetheless, the principle does appear to be valid for finite changes in temperature and pressure.) The present analysis provides for a deeper understanding of chemical reaction equilibria and can form the basis of several stimulating lectures and problem-solving sessions.

As a final note, a general statement concerning the direction of shift for changes in temperature of arbitrary amounts at constant pressure can be formulated. Assuming that the heat of reaction is always positive or negative, then an increase in temperature of any amount will cause the equilibrium to be displaced in the direction of the heat of reaction. A similar statement appears to be possible for pressure changes at constant temperature and depends on which direction the volume changes upon reaction. The addition of reactants and/or products, however, requires care, and in these cases it is not possible to formulate a general statement that is universally valid for any addition of products or reactants.

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REFERENCES

Mixing is a common operation in the process industries and is generally performed by a rotating impeller in a vessel. Products obtained from food, petroleum, mining, pharmaceutical, pulp and paper, and chemical industries would not be available without fluid mixing equipment and technology. Mixing also plays a vital role in industrial waste treatment and in environmental cleaning, such as in sulfur dioxide absorption for treatment of acid rain.\textsuperscript{[1,2]}

A wide range of mixing situations can be found in practice, which may involve high- or low-viscosity fluids, suspending solids in liquids, dispersing gas or solids in liquids, etc. Mixing operations at the industrial level are increasingly carried out at low to moderate Reynolds numbers, leading to segregated or dead regions and resulting in long mixing times. The simplest way used to improve mixing efficiency consists of increasing the rotational speed, which unfortunately leads to higher energy consumption. Mixing times in small-scale stirred tanks are commonly measured by non-intrusive techniques such as colorimetry. This technique also allows observation of the aforementioned segregated regions and how they tend to disappear as the impeller speed increases.

The objective of the mixing laboratory is to give students practical experience in the fluid mechanics of mixing by analyzing power consumption and mixing times associated with radial and axial flow impellers with Newtonian and non-Newtonian fluids.

The mixing laboratory is part of an undergraduate unit operations course offered by the Department of Chemical Engineering at Ecole Polytechnique of Montreal for senior-year students. Groups composed of a maximum of three students perform the required laboratory work in a period of four hours. The group prepares a preliminary report after finishing the experiments, and the students either hand over a full report or give an oral presentation the following week. Both the full reports and the oral presentations consist of a description of the experiment’s objectives, its theoretical basis, the engineering method used, the experimental setup, and the operating conditions. Then they present the experimental data, discuss the results, and make recommendations to improve the laboratory.

**EXPERIMENTAL SETUP**

The mixing system used in all the experiments is a modified Turbotest (VMI Rayneri) laboratory mixer, shown in Figure 1. It consists of a transparent polycarbonate vessel of 165-mm inner diameter and 230-mm height, with an open top fixed to a rigid table for safe operation. Two classical impellers are tested—a radial-flow impeller (6-blade Rushton turbine) and an axial-flow impeller (marine propeller). The impellers are mounted on a rigid shaft driven by a DC motor, with the speed carefully regulated in a range from 10 to 2500 rpm by means of a DC controller. The motor is mounted on a rigid structure that can be moved to adjust the vertical position.
The purpose of this experiment consists of determining the mixing time with two impellers providing different flow patterns. The mixing time, defined as the time needed to reach a specified degree of homogeneity, can be determined by various techniques...

 tion of the impeller. As can be seen in Figure 1, a standard mixing configuration is used as a starting point, with the impeller placed on the vessel centerline at 1/3 of the liquid height. The agitation torque is measured by a non-contact type torquemeter (range between 0.1 and 1.42 N.m) fitted between the motor and the agitation shaft.

Newtonian fluids consist of aqueous solutions of corn syrup having a viscosity of 1.5 Pa.s, while aqueous solutions of carboxy methyl cellulose (CMC) are employed as non-Newtonian fluids. The mixing times are measured with a colored tracer consisting of Methylene Blue diluted in both solutions. The two solutions, together with the tracer, are prepared prior to the experiments and allowed to settle at least 24 hours in order to eliminate air bubbles. The rheological properties of the fluids are determined by a Bohlin Visco 88V viscometer using a concentric cylinder configuration. Rheological measurements and the experiments are performed at room temperature (around 24°C).

The cost of the laboratory mixer and the solutions used for the experiments is about $5,000 and $20, respectively.

EXPERIMENTS

Power Consumption

This experiment consists of determining the power consumption for both radial- and axial-flow impellers with Newtonian fluids. For that purpose, the fluid under study must be added to the H level of the tank (see Figure 1) then the mixer speed is set to zero rpm and the torquemeter to zero N.m. The impeller speed is gradually changed from 15 to 700 rpm, and the torque reading for each speed is used to calculate the power consumption by means of

\[ P = 2 \pi r N T \]  (1)

where \( r \) is the impeller radius in m, \( N \) is the rotational speed in rps, and \( T \) is the torque in N.m.

The power consumption is correlated to the impeller speed by means of the dimensionless power number (\( N_p \)) and the Reynolds number (\( \text{Re} \)), defined by

\[ N_p = \frac{P}{\rho N^3 D^5} \quad \text{and} \quad \text{Re} = \frac{\rho N D^2}{\mu} \]  (2)

where \( P \) is the power in Watts, \( \rho \) is the fluid density in kg/m³, \( D \) is the impeller diameter in m, and \( \mu \) is the dynamic viscosity in Pa.s.

The laminar and transition regimes must be identified after plotting \( N_p \) as a function of \( \text{Re} \) on a log-log scale; the constant \( K_p \) for each impeller can be calculated by

\[ K_p = N_p \text{Re} \]  (3)

Mixing Times

The purpose of this experiment consists of determining the mixing time with two impellers providing different flow patterns. The mixing time, defined as the time needed to reach a specified degree of homogeneity, can be determined by various techniques based on the measurements of concentration, density, electrical conductivity, temperature, or by colorimetry, optical methods, thermal method, etc. The colorimetry technique is a qualitative method to determine the mixing time by adding a small amount of a color tracer to the fluid that is being mixed. The overall fluid color will change, and mixing time corresponds to the time when the tracer is judged to have completely dispersed within the fluid. The detailed procedure for measuring the mixing time is:

1. Use the configuration shown in Figure 1 with the Rushton turbine.
2. Add fluid (aqueous corn syrup or aqueous CMC) up to the H level.
3. Prepare the color tracer solution by dissolving 10 mL of Methylene Blue in 100 mL of fluid to be studied.
4. With the mixer at rest, add 15 mL of the color tracer solution to the tank containing the fluid.
5. Set impeller speed at 100 rpm and switch the mixer on.
6. Measure the mixing time at this speed.
7. Repeat Steps 3 to 5, using different speeds. The speed range
for this experiment is from 100 rpm to 600 rpm, with increments of 100 rpm.

8. Repeat the experiment for the marine propeller.

As proposed by Moo-Young, et al.,[5] mixing time can be correlated with the impeller speed by means of a dimensionless mixing time defined as

\[ N_{t_m} = \alpha (Re)^\beta \]  \hspace{1cm} (4)

where \( t_m \) is the mixing time in s, N is the impeller speed in rps, Re is the Reynolds number, and \( \alpha \) and \( \beta \) are adjustable parameters.

**Shear Rate of non-Newtonian Fluids**

The purpose of this experiment is to find out the effective shear rate for non-Newtonian fluids in the vicinity of the impeller by the Metzner-Otto correlation.[6] They developed a general relationship to correlate the impeller speed and the shear rate of a non-Newtonian fluid in the laminar regime. Based on the single knowledge of the power curve for Newtonian fluids, this relationship can be used to interpret and correlate power draw data for non-Newtonian fluids. This method assumes that there exists an average mixer shear rate developed in the vicinity of the impeller, which corresponds to the power consumption. This shear rate is directly proportional to the impeller speed through

\[ \dot{\gamma}_A = k_s N \]  \hspace{1cm} (5)

where \( k_s \) is the mixer shear rate constant.

The average shear rate, \( \dot{\gamma}_A \), defines an apparent viscosity, which is used in the definition of the Reynolds number for power consumption prediction for non-Newtonian fluids. The apparent viscosity is determined from viscometric measurements at the appropriate shear rate and used directly for plotting the power curve. The determination of the average shear rate, \( \dot{\gamma}_A \), involves the following steps (see Figure 2):

1. For a given impeller speed, a power number (\( Np' \)) is calculated from the P vs. N for non-Newtonian fluids.
2. Using this power number, \( Np' \), a Reynolds number (\( Re' \)) is obtained from the power number-Reynolds number correlation for Newtonian fluids.
3. Finally, the average shear rate can be determined from the viscometric data and, using the impeller speed, the mixer shear rate constant, \( k_s \), can be calculated from Eq. (5).

The procedure for this experiment consists of the following manipulations:

1. Mount the Rushton turbine at the end of the shaft and locate it in the center of the vessel, as in the first experiment.
2. Add the aqueous CMC to the H level.
3. Gradually change the speed, record the torque for each speed, and calculate the impeller power consumption from Eq. (1).
4. Plot the power consumption (P) vs. impeller speed (N).
5. By using the viscometer with the same fluid, record the apparent viscosity for each shear rate and plot the \( \mu_A \) vs. \( \dot{\gamma}_A \) curve.
6. Following the steps mentioned above, determine the average shear and calculate the mixer shear rate constant \( k_s \) from the Metzner-Otto correlation (Eq. 5).
7. Repeat the experiment using the propeller.

**FULL REPORT AND ORAL PRESENTATION**

As mentioned before, students are asked to prepare a preliminary report after finishing the experimental work. A week later they must deliver a full report or give an oral presentation. The full reports must contain

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**Figure 2. Determination of the shear rate constant \( k_s \):**

(a) non-Newtonian power consumption, (b) Newtonian power consumption, (c) non-Newtonian viscometry.
An abstract, including the objectives, the methodology used to achieve the objectives, and results and conclusions in relation to the proposed objectives.

The objectives must be clearly stated.

A theoretical perspective different from the one presented in the laboratory manual.

Main results for discussion and analysis, including graphs and tables. An example of a set of experimental data obtained by students is shown in Figures 3 and 4. The power curves in terms of the dimensionless power number (Np) as a function of the Reynolds number (Re) are shown in Figure 3. After performing linear regression with the experimental data, a good correlation can be observed between Np and Re. It must be noted that a slope of -1 should be obtained between Np and Re corresponding to the laminar region. An error of 5.47% and 0.53% in the slope is obtained for the Rushton turbine and the propeller, respectively. Figure 4 shows the dimensionless mixing time as a function of the Reynolds number for both impellers with a Newtonian fluid. From the linear regression results, it can be observed that the larger coefficients α and β correspond to the Rushton turbine, which is in good agreement with the results reported in the literature.

Interpretation, analysis, and discussion. These elements should be presented in great detail in a quantitative way, including the experimental error encountered. In the case of the experiments of power consumption and shear rate of non-Newtonian fluids, the torque should be measured at least three times in order to determine the experimental error.

Recommendations. This feature is used as feedback channel, so the students should suggest another experiment to perform or modifications to the experimental setup in order to improve the experiments.

Appendix. All the raw data must be presented so the reviewer can verify if the data were well processed.

On the other hand, the oral presentation is evaluated in terms of the form and the content. The introduction and objectives, presentation structure, illustrations, conclusions, and questions are all considered in the form. The subject knowledge, theoretical basis, and references and analysis capability are considered as parts of the presentation.

CONCLUSION

Because mixing is a unit operation involved in many industrial applications, a good understanding of this operation is central for a successful process. The proposed experiments give the students a general introduction to the fluid mechanics of mixing with Newtonian and non-Newtonian fluids, using impellers that provide different types of flow. In fluid mixing technology, as in other process design areas, dimensionless groups are used to correlate scale-up parameters. For that reason, experimental results must be presented in terms of these dimensionless numbers to be useful to the process designers. The proposed mixing experiments enable engineering students to gain excellent insight into the use of dimensionless groups.

REFERENCES


DEVELOPMENT AND IMPLEMENTATION OF AN EDUCATIONAL SIMULATOR: GLUCOSIM

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Illinois Institute of Technology • Chicago, IL 60616

The quality of student learning can be enhanced significantly by simulation of complex systems with user-friendly software. Complex real-world problems and solutions can be introduced to students by using simulation systems to conduct virtual experiments. These virtual experiments are especially useful when their real-world analogs are expensive and/or dangerous.

Simulation involves the use of the model of a system to observe the system’s response to changes in properties and inputs to the system. Simulations can introduce realistic problem situations and support a particularly active form of learning by letting students manipulate the conditions of the system and observe the consequences of those variations. The availability of a reliable and realistic mathematical model is essential to conduct simulations and understand the behavior of the system.

We have developed a dynamic simulator for glucose-insulin interactions in a healthy person and a Type-1 diabetic patient. The aims of this public domain simulator are to provide assistance to bioengineering students in learning glucose-insulin interactions in the human body, to offer a tool for engineering students in learning system dynamics, and to provide an illustrative tool to diabetic patients. The simulator cannot be used for adjusting a patient’s insulin dosage regulation in real life, but may be helpful for patient education.

Both MATLAB-based-stand-alone and web-based graphical user interfaces (GUI) are software designs that yield interactive systems. Despite many similarities between the two designs, there are also many differences. Simulators with web-based GUIs are more accessible over the internet, but stand-alone software can also be distributed widely while giving the developer/designer an opportunity to keep track of the users. Furthermore, since the stand-alone GUIs are in a defined frame, the designer controls where the user goes when browsing among the links, while in web-based GUIs, the user has all the control and in many typical situations there is a high possibility that he or she may branch out to an arbitrary website while browsing.

Modeling glucose-insulin interactions requires an understanding of the physiological and metabolic processes that determine observable behavior. Mathematical models describing carbohydrate metabolism are available in the literature. We have used and extended two mathematical models based on pharmacokinetic diagrams of glucose and insulin in the human body. Mass balances for both glucose and insulin resulted in a set of ordinary differential equations, and the models are implemented in a computer program written in MATLAB 5.3. The mathematical details of these models are available elsewhere. ODE23 (low-order Runge-Kutta routine) is used for solving differential equations. The models are then integrated with a GUI that is responsible for presenting information to the user in a clear and friendly way.

Fetanet Ceylan Erzen
received a BS degree in chemical engineering from Middle East Technical University (1999) and an MS degree from Illinois Institute of Technology (2000). Her thesis studies included modeling and simulation of glucose-insulin interaction in the human body and graphical user interface development. Gülner Birol received BSc, MSc, and PhD degrees in chemical engineering from Bogazici University in 1990, 1992, and 1997, respectively. Her current research interests include glucose biosensors, investigation of retinal vascular occlusion, and the relationships between oxidative and glycolytic metabolism in the retina on animal models. Ali Çinar received a BS degree in chemical engineering from Robert College, Turkey (1970), and MEng (1973) and PhD (1976) degrees from Texas A&M University. His teaching and research interests are process modeling and control, statistical process monitoring and fault diagnosis, and use of knowledge-based systems for real-time process supervision and control.

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SIMULATOR

1 System Availability

GLUCOSIM was originally developed in MATLAB 5.3.1 on a PC platform. It requires three MB of hard disk space. A demonstration of the package is available on the web at <http://www.chee.iit.edu/~control/software>. The simulator can be obtained by writing to Ali Cinar (e-mail at cinar@iit.edu).

1 User Interface Design

A computer is limited not by its power to compute, but rather by its power to communicate with its human users.[6] The main requirement for wide acceptance and use by the students is an easy-to-learn, easy-to-use efficient interface.[7] A simple and natural dialogue for modern computer systems with GUIs can be achieved by a good graphic design[8] and consistent screen layouts. Several guidelines are followed for this purpose while designing the GUI in this work:

- Consistency of the user interface. Similar objects and colors are used to perform similar functions throughout the simulator to facilitate recognition. If users know that the same command or the same action will always have the same effect, they will feel more confident in using the system.[9] Also, the design is limited to a small number of consistently applied colors.
- Ease of navigation. The user is able to navigate without getting lost or worrying about causing harm.
- Importance of help and documentation is kept in mind. If students need to refer to documentation for help or for background information, there is sufficient and comprehensive, but brief, documentation throughout the simulator. Navigation is also available between the documentation; for example, users can return to the tutorial while reading a help file.
- Dialog boxes have a quit and/or back button. This gives users a feeling of being in control since the user rather than the computer decides where to go, what to see, and when to leave.

The structure of the simulator is illustrated in Figure 1 and its capabilities are outlined in Table 1. There are three categories of windows in the simulator: information windows, transition windows, and input/output windows. A detailed description of these windows is presented later in this paper.

1 Model Equations

The pharmacokinetic models for glucose and insulin are based on mass balance equations on various physiological compartments such as heart, lungs, and arteries (H), nervous system (NS) (for glucose), or subcutaneous tissue (SC) (for insulin), liver (L), pancreas (PN), gastrointestinal tract (GT), kidney (K), and periphery (PR) (skeletal muscle and adipose tissue). For example, the circulating blood insulin concentration, $I_B$, is described by

$$V_B \frac{dI_B}{dt} = Q_{SC}(I_{SC} - I_B) + Q_K(I_K - I_B) + Q_{PR}(I_{PR} - I_B) + Q_L I_L - (Q_HA + Q_{PN} + Q_GT) I_B$$

where $Q$ denotes the blood-flow rate (dl/min), $V$ denotes the volume (dl), $t$ denotes time (min), and $I$ denotes the insulin concentration (mg/dl). Subscripts B and HA denote blood and hepatic artery, respectively. The mass balance in subcutaneous tissue is

$$V_{SC} \frac{dI_{SC}}{dt} = Q_{SC}(I_B - I_{SC}) + r_{IA}$$

where $r$ denotes a metabolic source or sink rate, and the subscript IA denotes insulin absorption. The detailed model consists of a system of ordinary differential equations represent-
ing mass balance equations in all compartments. The overall model is derived by assuming that the mass balances in each tissue are in quasi-steady state (i.e., dI/dt = dG/dt = 0). The resulting algebraic equations for glucose and insulin concentrations are combined into the glucose and insulin balances in the blood, yielding an overall model with two differential equations.

Two models of insulin release were taken from the literature, modified, and used in the current simulator for healthy humans. The first one is based on islet insulin secretion model developed by Nomura, et al.\textsuperscript{10} for rat islets, and the second one is based on the pancreatic insulin release model developed by Carson and Cramp.\textsuperscript{11}

### Features

A MATLAB-based, user-friendly GUI was designed and integrated with the MATLAB code written for the mathematical model. The interaction of the user with the software has been kept as simple as possible. Menus, buttons, and sliders are widely used as controlling elements. Values are displayed graphically with a “save” option. “Help” windows throughout the program are available and the user can quit the program at any time. Furthermore, the simulation can be stopped at any time by using the “stop” button on the simulation progress bar. The main window (see Figure 2) is designed to familiarize the user with the environment.

There are three buttons—“About,” “Tutorial,” and “Background Information.” The “About” button gives a brief introduction to the program; “Tutorial” provides information about the model used, along with a short literature review; and the “Background Information” button is linked to another window where it is possible to search for the definition of a word related to diabetes from the database created (Figure 3) to view the relevant web links (Figure 4) or to get information about the references used on the development of both the mathematical model and the simulator.

By using the “NEXT” button placed in the bottom left-hand side of the main window (see Figure 2), the user can choose between “DEMO” and “SIMULATOR” modes. The purpose of the DEMO, which consists of snapshots, is to give the user a general idea of the simulator’s capabilities and a preview of how the simulator functions. By selecting the SIMULATOR mode, the user goes from the “information” mode to an “experiment” mode. Here, there are three options for the virtual experiments. The first option performs the “Oral Glucose Tolerance Test” (OGTT), the second and third opt...
tions simulate a “Healthy Person” and a “Diabetic Patient,” respectively. The user has the flexibility to choose between the two different models for the healthy mode (Model I and Model II) and between the two different models for the Type-1 diabetes mode (detailed model and overall model).

For OGTT, the only input is the weight of the person. There is also an option where the user can load his or her own previously saved data. Inputs for the other two modes (Figures 5 and 6) are

1. Carbohydrate content of the meal. There is also a nutritional database where the user can find the carbohydrate content of a specific meal.
2. Time of meal and injection. The user can enter a value between 0-24 hours for time of meal and insulin injection.
3. Insulin type and dose. Two types of insulin are available, i.e., regular and ultralente.
4. Body weight
5. Duration of exercise. The exercise option, which is specifically designed for moderate exercise, is available for only Type-1 diabetes mellitus mode.
6. Duration of simulation. It is possible to simulate the dynamics of the diabetic patient and a normal person for a maximum of 24 hours with up to four injections in diabetes mode.

The outputs of the simulation are displayed by continuously updating the figures displayed on the screen (Figure 7). Once the simulation is finished, data can be saved in ASCII and/or graphic form to make the recall and display of the profiles possible for further analysis.

IMPLEMENTATION

1. Overview of the Course

The course focuses on application of engineering principles to biochemical and biomedical systems. Biochemical engineering topics include biological systems, enzymes and microbial kinetics, and design and analysis of biological reactors. Biomedical engineering topics include flow properties of blood, transport in human cardiovascular systems, and analysis and design of artificial organs. Half of the semester is spent on biomedical engineering, while the other half is used for biochemical engineering. Details of the course are documented elsewhere. The average number of students registering for this class is around twelve every semester.

The primary learning goals of the course are to provide students with basic principles in cellular biology of microbial cells, bioreactor operations and transport phenomena in living systems, and enzyme and microbial kinetics and pharmacokinetics—in short, to provide them with a working knowledge of bioengineering applications.

The course was designed to achieve these learning objectives that were assessed using fairly traditional methods (i.e., homework assignments, examinations, and term projects)

Figure 5. Main window for Type-1 diabetes mode.

Figure 6. Main window for healthy person mode.

Figure 7. Output window.

Fall 2003
throughout the semester. The class has been taught by the same instructor for three semesters at IIT and has been updated from semester to semester to better meet the learning objectives and the needs of the students in an effective learning environment. During this time, it has become a popular course. The overall rating of the instructor and the course increased 18% and 31%, respectively, since its inception. It was rated 15% and 12% higher when compared to the average instructor and average course ratings of the department (Chemical and Environmental Engineering Department), respectively.

**Implementation of the Simulator**

Previously, the beta version of the simulator had been tested in the course in the Fall '99 semester.[13] Based on the feedback provided by the students, MATLAB codes were updated and the gamma version was integrated into course material in the Fall '00 semester.

This was one of the term projects in which students were expected to use the simulator for a period of two weeks, and it formed 7.5% of the class grade. The simulation package, which was distributed to students on a CD, was introduced immediately after the pharmacokinetics topic had been covered in a series of lectures. Distributing the software on CDs helped students work from home as well as from different PCs as long as they had MATLAB software installed.

The students were asked to run a series of simulations at different conditions, and the choice of models was left up to the students so they could have the opportunity to investigate the part(s) they wanted and were most interested in. Their interests varied significantly. Some tried all the combinations (described in the Features section), while others focused on investigating a single issue (e.g., the effect of body weight on glucose levels).

At the end of the two-week exposure to the simulation package, a class discussion was organized where students could share their experiences with the simulator, talk about their findings, and make conclusions in an informal discussion setting. During the two-week period, the instructor and a graduate student were available outside of class to as-

---

**TABLE 2**

Survey Questions for the Project

<table>
<thead>
<tr>
<th>Question</th>
<th>Average</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. How could the simulator and GUI be improved?</td>
<td>4.22 ± 0.67</td>
<td></td>
</tr>
<tr>
<td>2. How computer literate do people need to be in order to use the simulator?</td>
<td>3.66 ± 0.71</td>
<td></td>
</tr>
<tr>
<td>3. How much do people need to know about human physiology in order to benefit from the simulator?</td>
<td>2.11 ± 0.78</td>
<td></td>
</tr>
<tr>
<td>4. In your opinion, does the product have any educational (or other) value?</td>
<td>4.11 ± 0.93</td>
<td></td>
</tr>
<tr>
<td>5. What did you learn from the project? What else would have been interesting to learn?</td>
<td>4.00 ± 1.00</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 3**

Survey Questions and Responses for the Simulator

<table>
<thead>
<tr>
<th>Question</th>
<th>Average</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. This simulator is a helpful learning tool: disagree(1)...strongly agree(5)</td>
<td>4.55 ± 0.52</td>
<td></td>
</tr>
<tr>
<td>2. Your comments related to the system experience:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Your comments related to terminology and system information:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Your comments related to system capabilities:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Your comments related to Background and Technical Info:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Your comments related to Simulator:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
sist students. Some students had difficulty uploading the software, so extra meetings were arranged to overcome and minimize any technical difficulties. The instructor also encouraged students to visit her outside of class and to discuss the progress of their projects. Most students showed a high interest in the course during this period because they were able to integrate textbook topics with real-life situations.

In order to assess the educational benefits that the simulator provided, a discussion session that took one lecture hour was conducted by the instructor, students handed in individually prepared written reports at the end of two weeks, and a survey was prepared and administered at the end of the project. Table 3 lists the questions that were targeted to serve as a tool for refinement of the simulator and summarizes students’ responses to the survey questions.

Furthermore, to assess the simulator’s design capabilities, a questionnaire based on earlier works on software and courseware design and evaluation[14] was developed and administered at the end of the project. Table 3 lists the questions that were targeted to serve as a tool for refinement of the simulator and summarizes students’ responses to the survey questions.

Students commented favorably on the project and the simulator. Most of them thought they better appreciated the application of theories that they learned in the biomedical section of the course, that they learned the difference between a healthy person and a diabetic person, that the project was stimulating because it allowed them to do something other than calculations or a report, and that it gave them an opportunity to experience a practical application of pharmacokinetics in a real-life problem. They felt that even though it took them some time to start working with the simulator, its clarity made the project interesting. Some of the students provided feedback on typographical errors and improvement of the GUI.

Furthermore, students identified the simulator as a great learning tool for open-ended real-life problems. They found it interesting to input their own daily diet and see how their glucose rates changed throughout the day. They also found the exercise option interesting. Some of them were even amazed at how MATLAB software could be turned into such a user-friendly form and could be used in such a practical way.

CONCLUSIONS

The purpose of this article is to share an educational tool based on glucose insulin interactions in the human body. A simulation package was integrated into an Introduction to Bioengineering course and was assessed for its efficacy through assigning a term project that allowed students to explore glucose insulin interactions in the human body with the aid of a simulator. Further assessment of the simulator has been carried out via surveys for additional improvement and refinement. These data are in the form of questionnaires completed at the end of the term project. The course is being refined based on student and expert feedback, and examination problems that address the learning objectives of the simulator are being developed to better assess the simulator’s effectiveness as a learning tool. A web version of the software has also been developed that will provide an opportunity to serve and obtain feedback from other student communities.

ACKNOWLEDGMENTS

The authors are grateful to Drs. J. Abbasi an, I. Birol, V. Perez-Luna, and C. Undey of IIT and Peter J. Reilly of Iowa State University for their valuable suggestions. Financial support provided by NSF (EEC-0080527) is gratefully acknowledged. Special thanks to the Fall 1999 and 2000 students for their feedback.

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Simulation and Experiment in
AN INTRODUCTORY
PROCESS CONTROL LABORATORY
EXPERIENCE

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There are several advantages to integrating classroom and laboratory exposure. For many students, understanding concepts taught in the classroom improves significantly when they have the opportunity to gain hands-on experience in a laboratory. A laboratory exercise also provides an opportunity to apply the theory they have learned in the classroom to an actual engineering problem. Finally, comparing experimental data and dynamic simulation results is an effective way to reinforce process dynamics education in a laboratory exercise. The wider incorporation of process dynamics into the curriculum is considered to be a key component in process control education of chemical engineering students.\(^1\)

There are a number of simulation-based chemical process dynamics experiments presented in the engineering education literature. They range from modules incorporated into a commercial process control computer system,\(^2\) case studies illustrating various process control concepts programmed using MATLAB/SIMULINK,\(^3-5\) and workshops based on real-time simulation of industrial unit operations.\(^6\) Although there are benefits of simulation-based experiments, a major disadvantage is the lack of an actual physical process that the students can watch, hear, and touch while it is operating. Understanding the dynamic behavior of a process is greatly enhanced by observing the physical process operation. Visualization provides a significant benefit to many students as they attempt to apply the theoretical concepts taught in the classroom.\(^7,8\) This aspect was one of the main motivations for developing the experience documented in this work.

A review of the equipment-based chemical process dynamics experiments presented in the engineering education literature reveals a wide range of complexity in the processes considered. They range from relatively simple liquid-level\(^9\) and stirred-tank\(^10\) systems, multiple tank systems,\(^11\) quite complex reaction\(^12\) and distillation\(^13\) systems, and combinations of simple, more complex, and simulated systems.\(^14\) Because this experience is intended to be an introductory exposure to process dynamics, simulation, and control, using an easily modeled, simple, physical process that incorporates the introductory concepts from the process control and simulation course is appropriate. For this reason, a single-tank liquid-level system was chosen.

Feedback control is performed using a proportional-only controller. Proportional control provides two benefits for this introductory experience. The first is that a proportional controller is easily simulated. The additional complexity required in the simulation of integral action in the controller provides little, if any, benefit to the understanding of process dynamics and dynamic simulation in an introductory experience. The second benefit is that proportional control results in steady-state offset of the tank level. This concept is often difficult for some students to initially grasp in the classroom. The ability to observe this phenomenon on a real physical system can be very helpful for these students.

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For many students, understanding concepts taught in the classroom improves significantly when they have the opportunity to gain hands-on experience in a laboratory. A laboratory exercise also provides an opportunity to apply the theory they have learned in the classroom to an actual engineering problem.

LABORATORY EQUIPMENT

The experiment is carried out using a 50-gallon gravity-drained tank equipped with liquid level and outlet flow sensors. Liquid level is controlled by a valve on the inlet water pipe. There is an additional inlet water pipe with a manual valve. The outlet flow rate can be adjusted by a manual valve on the outlet pipe of the tank. A steam heater is connected to the tank but not used in this experiment. The tank is 2.5 feet in height and 1.8 feet in diameter. The tank system is shown in Figure 1.

Liquid level control is provided by a single-loop electronic controller. There is also a distributed computer control system connected to the tank. Because we believe there is value in exposing the students to both the single-loop electronic and computer control systems, we have the ability to switch between the two systems on this tank. The single-loop controller is used for this introductory experiment, while the computer control system is used for temperature-control experiments and a model predictive control experiment in the senior laboratory course.

LABORATORY EXERCISE

The exercise comprises two three-hour laboratory sessions. During the first session, the student groups become familiar with the tank system and perform the experimental work. In the second session, they develop their dynamic simulation model, compare their simulated results with those obtained experimentally, and document their findings in a short memo report to the instructor.

The laboratory exercise begins with the tank operating at steady state under proportional-only feedback control with a water level setpoint of 50%. The instructor reviews the physical operation of the tank, goes over each component comprising the feedback control loop, and leads a short discussion concerning the options to remove steady-state offset with the student group. The students are then instructed to adjust the controller bias to remove the steady-state offset in the tank level. They may either put the controller in manual and adjust the control valve position or adjust the bias directly to eliminate the offset. The value of this exercise is gaining an appreciation for the response time of a real physical system. The students are prompted to estimate both the time constant of the system, which is on the order of five minutes, and the open-loop response time of the tank in order to determine how long it should take for the tank level to reach steady state after a change to the inlet water valve position is made. Although process simulators provide valuable training experience for the students, a major drawback is that those experiences are in "simulation" time. The first part of this laboratory exercise demonstrates that real process dynamics are not on this same simulation time scale.

After the students have adjusted the bias to eliminate the steady-state offset in the tank level, the system is returned to closed-loop control and they are allowed to choose one disturbance from a list in the laboratory instructions. This list contains the following disturbances:

- Simultaneously dump two small buckets of water into the tank
- Dump one large bucket of water into the tank
- Change the inlet flow rate by opening the manual disturbance flow valve
- Change the outlet flow rate by opening or closing the manual outlet valve
- Change the level setpoint
- Change one of the level controller tuning parameters

where the two small buckets are each two gallons, resulting in an impulse disturbance that is approximately 20% of the liquid volume; the large bucket is 25 gallons, resulting in an impulse disturbance when full that is about the same as the liquid volume; and the disturbance flow results in a step change to the outlet water valve position.
disturbance that is about the same as the initial steady-state inlet flow rate.

From the instructor’s perspective, it is desirable to have as much variation in the selected disturbances between groups as possible to make the students’ semester-end oral reports on this experiment more interesting. In practice, other than discouraging the one large bucket, prompting by the instructor in order to provide this variation has seldom been necessary.

Prior to implementing their chosen disturbance, the tasks of time keeper, data logger, and disturbance initiator are distributed by the group members among themselves. Their selected disturbance is then implemented on the tank system under closed-loop level control. The initial data point is collected after the disturbance has been completed. In the case of the buckets, this point is the time when all of the water has been emptied into the tank. Because two students (and sometimes the instructor) are required to empty the bucket contents into the tank, the time-keeping and data-logging tasks are performed by one student at the beginning of the experiment. For the other disturbances, the initial data point is taken immediately after the valve position or controller tuning parameter has been changed. Data is collected at intervals of ten to twenty seconds until the tank level reaches steady state. The experimental phase of this exercise is typically completed well within the three-hour laboratory period.

**PROCESS SIMULATION**

The second phase of this exercise involves the dynamic simulation of the closed-loop tank system with the disturbance chosen by the group. This phase is carried out during the laboratory period immediately following the experimental session. Process simulation begins with an unsteady-state material balance over the tank. Assuming a constant cross-sectional area of the tank, $A_c$, and the same constant density for all water streams, a macroscopic mass balance results in

$$A_c \frac{dh}{dt} = F_{in} - F_{out}$$

(1)

where $h$ is the height of water in the tank, $F_{in}$ is the inlet volumetric flow rate, and $F_{out}$ is the outlet volumetric flow rate.

The inlet volumetric flow rate of water is determined by the position of the control valve. Although this control valve is linear, the inlet flow rate is not a linear function of valve position over the entire valve position range due to variation in the water supply pressure as the valve position changes. The students are given a calibration curve, shown in Figure 2, that is used to relate the inlet flow rate to the control valve position. Over the linear operating range of the valve, the following correlation can be used to determine the inlet flow rate

$$F_{in} = 0.171(V_p)^{1.03} \quad 10 \leq V_p \leq 60$$

(2)

where $F_{in}$ is the flow rate in units of gpm and $V_p$ is the control valve position in units of % open. If the disturbance flow was selected, there is a second constant inlet flow rate that must be added to this relationship.

The outlet volumetric flow rate is assumed to be proportional to the square root of the pressure drop across the manual outlet valve due to the static head of fluid in the tank

$$F_{out} = K_v \sqrt{h + \frac{19}{12}}$$

(3)

where $F_{out}$ is the flow rate in units of gpm, $K_v$ is the proportionality constant, $h$ is the height of the water in the tank in units of feet, and the bottom of the tank is 19 inches above the outlet valve. The proportionality constant $K_v$ is determined from the measured outlet flow rate and water height when the tank level is at steady state.

The control valve position is determined by the level controller on the tank. For the proportional-only controller, the valve position is determined from the controller equation

$$V_p = B + K_c(S_p - L)$$

(4)

where $V_p$ is the valve position in units of % open, $B$ is the controller bias in units of % open, $K_c$ is the proportional gain in units of % open/% level, $S_p$ is the water level setpoint in units of % level, and $L$ is the level of the water in the tank in units of % level. In practice, the controller gain is kept at a value around 1 %/% to prevent the control valve position from moving out of its linear operating range during the transient response due to the disturbance.

Simulation of the process is carried out by numerical solution of Eqs. (1) through (4). Before they can be solved, however, the units must be made consistent throughout all of the

![Figure 2. Inlet water control valve calibration curve.](image-url)
relationships. The controlled variable for the controller is configured to be in units of % while the tank dimensions are given to the students in units of feet and the flow rate calibrations are given in units of gpm. This variation in the units given to the students is intentional. Numerical solution is typically carried out by the student groups using MathCad, which is used by the department in the introductory material balance and the numerical methods prerequisite courses, although they are free to use any of the other mathematical software packages such as MATLAB, EXCEL, and Maple that are available on the engineering college server.

EXAMPLES AND DISCUSSION OF RESULTS

Example experimental and simulation results are shown in Figures 3 and 4. Figure 3 presents the results for the large bucket impulse disturbance. In this example, the large bucket was only about half full. Figure 4 presents the results for a reduction in the outlet flow rate from closing the manual outlet valve. In both cases, the experimental and simulated responses are very similar. These results are typical for most of the student lab groups.

In addition to presenting their experimental and simulation results, the student groups are asked to discuss the sources of error in this experiment in their group memo report. Examination of the experimental and simulated dynamic responses reveals that the simulation leads the experimental response. Because there are dynamics associated with the level sensor and control valve that are not included in the simulation model, this result would not be unexpected. The effects of valve friction, sensor noise, and the precision of the liquid level value displayed by the controller can also contribute to error as well as the assumption of a perfect square root relationship and a constant $K_v$ value for the outlet flow rate that may not be valid over the liquid level ranges encountered in the experiments. Experimental error in the timing of the collected level data samples is also present. Almost every student group mentions the valve, sensor noise, and sampling error as sources of error in their report. Some groups also mention the outlet flow relationship used in the simulation model. Few groups discuss the dynamic effect of the valve and sensor.

STUDENT RESPONSE

As part of the student evaluation of the process simulation and control course, a number of supplemental questions concerning the value of the text and controller simulation software used in the course, the laboratory experience documented here, and the preparation received in the required prerequisite courses are included. The evaluation scores ranged from 5=Very Effective to 1=Very Ineffective. The average scores from the last four years are: presentation and explanation of concepts in the textbook, 3.04; use of CStation for class examples, 3.25; use of CStation for homework problems, 2.96; process control experiment in Lab II, 4.02.

CStation[^18] is the process control simulation software package used in the course, *Essentials of Process Control*[^17] was the course text at the time of these evaluations, and the process control experiment in Lab II is the experience documented in this work.

The average score given by the students for this laboratory experience is considerably higher than for the text and process control simulation package and is essentially the same as the average score of 4.10 for the value of the process control and simulation course over the same period. It should be noted that a number of students have provided somewhat negative comments concerning the length of the loop tuning homework assignments requiring the use of CStation. These feelings may have had some influence on the CStation scores. It should also be noted that only one
RETURNING AS A PROFESSOR

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Chemical engineering departments should stay in contact with industry so their students can be taught material that is useful after graduation and so research will be relevant to the needs of industry. Unfortunately, very few of the professors being hired from graduate schools or after post-doctoral experiences have significant industrial experience. In this article we will discuss one way to maintain this contact—by bringing back experienced engineers from industry as post-early retirement Industrial Professors or Engineers in Residence. These individuals should be integrated into all aspects of teaching and research within the department. This article is based on the experiences of one of the authors (GB) who joined the School of Chemical Engineering at Purdue University during the spring semester of 1998 and who has served in the Industrial Professor role since that time. The results are generalized for other "wannabe professors" from industry who are contemplating a career shift, as well as other chemical engineering departments considering initiating such an infusion of industrial talent.

MOTIVATION, OR THE ADVANTAGES FOR THE INDUSTRIAL GUY

Dr. Gary Blau had a successful industrial career with the Dow Chemical Company, primarily on the technical ladder. A Canadian, Gary graduated in 1964 from the University of Waterloo with a BASc in chemical engineering and went on to get his PhD at Stanford University in 1968. He then went to work with Dow Chemical. In 1991, he accepted an offer to work with DowElanco (now DowAgrociences), a joint venture between the agrochemical business interests of Dow Chemical and Eli Lilly.

At DowElanco, his final assignment was leading a group of six engineers in the development and application of mathematical modeling tools to optimize work processes within the company. He remained professionally active by writing over fifty journal articles, coauthoring a book on mathematical modeling, editing another on Environmental Exposure to Chemicals, organizing meetings, and serving in various leadership roles in the Computing and Systems Technology (CAST) division of AIChE. In 1998 he won the Computing Practice Award from AIChE.

Why, then, did a highly successful, mid-career engineer decide to take early retirement for a lower-paying, temporary position? The answer embraces timing, location, opportunity to develop a business, fulfillment of a dream, and idealism. Gary's sponsor had just retired, and the resultant lack of management support made fighting for proper recognition for his group increasingly stressful. In other words, the job was not much fun any more. After thirty years of experience, he was eligible for early retirement—so he began to look for new challenges.

Gary, like many PhD engineers in industry, was a "closet academic." Going to academe would fulfill the academic dream that all Stanford graduate students harbor. A model for this ambition was Dr. Park M. Reilly, who had worked in...
His primary motivation, however, was his desire to be the faculty “industrial guy” and to share his real-world experiences with future engineers. He felt he could prepare the chemical engineering students for what industry is really like.

industry for 25 years before pursuing a successful academic career at Waterloo. Gary also had a desire to do independent consulting in the modeling area, but his networks and paper trail were too thin to support this activity.

His primary motivation, however, was his desire to be the faculty “industrial guy” and to share his real-world experiences with future engineers. He felt he could prepare the chemical engineering students for what industry is really like. He planned to develop “ill-defined, open-ended” problems and to teach the students how to use their engineering skills to solve them. He would train them in the proper use of statistical modeling, quality control, and risk management techniques so they could have an immediate impact in industry. He would show by examples and “war stories” that “soft skills” are really important in industry. Since Gary had developed and taught process optimization short courses to literally hundreds of Dow engineers and chemists around the globe, he felt his teaching skills were sufficiently honed to motivate students.

**BECOMING AN INDUSTRIAL PROFESSOR**

While at Dow Agrociences, Gary became involved in supply-chain optimization issues, resulting in joint research collaboration with Professor Joe Pekny at Purdue. Gary helped support some of Joe’s research, worked with him on organizing the Foundations in Computer-Aided Process Operations conference, and presented some lectures. He also knew Professors Rex Reklaitis and Nick Delgass (Head and Associate Head of Chemical Engineering, respectively) from their days as graduate students at Stanford. Since Purdue was a short 50-minute commute on the interstate, Gary decided to accept Rex’s offer to be a Visiting Industrial Professor.

The courses Gary would teach and his time commitment to Purdue were finalized during initial discussion with Rex. Gary felt that 2/3 time during the academic year, with summers off, would provide time for him to pursue both consulting and leisure activities. He identified a required core course he was well-qualified to teach and a new elective course he would like to develop. He would also become involved in the systems research program and help jointly direct the research program of some of Joe Pekny’s graduate students.

Once a mutually agreeable salary was determined, Gary became a Purdue professor. Since tenure was not an important consideration, the position was not on the tenure track—making it easier for the university to develop the position.

The process by which the new industrial professor and the institution found each other is probably transferable, so a list of the steps that took place is appropriate. First, the potential professor should generate a record of accomplishment in industry that is respected by the academic community. If research is to be part of the academic position, this industrial record must include an adequate publication record. There should be personal contact (networking) with some of the professors in the department. The applicant should become involved with the research program—sponsoring research is particularly helpful. He/she needs to give some lectures to undergraduate classes and, if appropriate, to the graduate research seminar.

After determining core undergraduate courses and one or more electives that he/she is qualified for and wants to teach, the applicant can make a proposal to the department head concerning time commitment, course assignments, research involvement, salary, etc. Since the question of tenure can be a major stumbling block, formal ties are easier to forge if a yearly contract is acceptable.

Of course, “making it happen” is not the sole responsibility of the industrial practitioner. The academic institution can also be proactive by identifying individuals who might be good candidates for the industrial professor program. A departmental representative can talk with the prospect about the program and determine if there is any interest.

**EXPECTATIONS VERSUS REALITY**

Like many other senior engineers, Gary frequently taught short courses, and since there had never been complaints, he believed he was prepared for teaching in a university. Although he hadn’t graded in these short courses, he expected that the grading scheme would be unchanged from what he had observed as a student or that he would be given clear instructions on how to grade. He expected the students would be courteous and neatly groomed. After all, he reasoned, they were in school because they wanted to learn and thus should be highly motivated to learn from someone who could show them the value of their education.

Gary assumed that the students would have the same strong technical background in mathematics and science as he and his classmates had thirty-five years ago. He expected to share his knowledge and thus prepare the students for careers in industry. He looked forward to building personal relationships with some of the students, and he viewed teaching as the most important role he would fill, with research being a secondary consideration. Since he was experienced, teaching just one class (even if it was a large class) three times a week would be a “piece of cake,” allowing him plenty of
time for other pursuits. Finally, it never occurred to him that
the students might challenge him.

Those were the expectations. The reality had a different
face. A book by Peter Sacks gives an accurate portrayal of
the trials of returning from the working world to become a
professor, and although he had read Sacks’ book, Gary thought
that engineering students would be different. That did not
turn out to be true. Unfortunately, many students believe that
if they do poorly, it’s the professor’s fault, not theirs. As a
new professor, Gary unwittingly played into this rationaliza-
tion for poor performance by giving tests that were difficult
and too long. With test averages in the 30s and 40s, the stu-
dents blamed Gary for their lack of preparation.

Gary also learned that many students seemed to be more
interested in the final course grade than they were in learning
the material. Since grading procedures were never well de-

dined for him, he tried to enforce what he thought were rea-

sonable grading standards, but some students argued con-

stantly with him in an effort to raise their grades.

Teaching evaluations were a new concept for Gary since
they had not been in use when he was a student, and he found
that some students used them to “dump” on a professor. He
worried that firm grading would be penalized when students
filled out the mandatory teaching evaluations. Also, being
connected on-line to the class allowed students to provide
immediate, often unflattering, feedback on Gary’s classroom
performance. Because of his position in industry, Gary had
always been insulated from direct criticism from subordinates,
and he found the harsh criticism from 19- and 20-year-olds
hard to accept.

Gary found that today’s students are different from those
of thirty-five years ago in other ways. For one thing, they
wanted to be entertained. Fortunately, he found that his ex-

perience was useful in this regard since the students enjoyed
listening to his industrial stories. He also found that the stu-
dents’ work ethic was low and that they were less comfort-
able with ambiguity. When he introduced his industrially in-
spired “open-ended, ill-defined” problems, many students
were frustrated with them, wanting instead problems that were
crystal clear and did not require assumptions.

Talking during class was also rampant and required special
control techniques that had been unnecessary in his small classes
in industry. To his surprise, some students were actually rude
and disrespectful. Some staff members also let Gary know that
as a visiting professor, he was at the bottom of the heap.

Gary found that teaching was much more difficult in aca-
deme than in industry and that it was difficult to learn
everyone’s name, let alone build a personal relationship with
them. Students in industry were more polite, more motivated,
and better prepared—they wanted to be in the educational
session, and any errors in presentation were quietly corrected.
But at the university the students were vocal about errors and
were unwilling to think their way through a derivation and
develop all the details by themselves.

While students in industry never complained about too
much material (apparently they sorted out for themselves what
was useful and what wasn’t), university students were over-
whelmed by the amount of material, and trying to introduce
new methods such as new software only made matters worse.
The resistance to change was much greater at the university
than it was in industry.

Testing was a challenge that had never arisen in industry.
Some students would become angry if they were unable to
finish a test, so creating one that was not too long became an
enormous challenge. Gary found that students often seemed
incapable of doing very simple problems, particularly if there
were multiple steps. Grading the exams took much more time
than he had anticipated, and Gary soon came to see the beauty
of short-answer problems. Student cheating led to Gary’s
general distrust of students, and he learned to place students
in alternate seats and to roam the classroom during exams.

Gary also found that teaching was more time consuming
than he expected. For the initial course offering, each 50-
minute lecture took over four hours to prepare, and the sec-
ond offering took almost as long because of the many revi-
sions that had to be made. An unexpected responsibility was
supervising two graduate TAs and eight undergraduate
TAs—Gary felt that he had traded six highly motivated
self-starters in industry for ten students who were just
“doing a job” for the money.

Since it was essential to be present for every class, teach-

ing meant a much less flexible schedule than Gary had had in
industry. It came as a surprise that in some ways, time pres-
ures were greater in academe than they had been in industry.

Finally, Gary found that at a research university, teaching
was not the top priority. It had to be adequate, but research
(specifically, research funding) was most important. Most pro-

fessors wanted to talk about research, not teaching.

LEARNING TO SURVIVE

The most important step to surviving is adaptation: reflect-
ing on what happens, sorting through the criticism, talking to
students and professors alike, revising, and doing it again.
Talking to students revealed that their pressures are much
different than they used to be—they are busier and many of
them work part-time. Fewer have strong backgrounds in
mathematics, chemistry, physics, or other areas of engineer-
ing, and fewer still are dedicated to becoming chemical engi-

neers. In talking to the students and professors, Gary also
found that he had not been singled out as a new professor for
criticism—it was more of an equal-opportunity endeavor, and
more important, there were methods to prevent it. There were
also approaches that would improve the course while at the
same time reduce the time required to conduct it.
Initially, Gary’s self-confidence was so badly shaken that he asked the associate head to team him with one of the more successful teachers in the department. Although this presented a scheduling nightmare, Gary was allowed to share his teaching responsibilities with Joe Pekny, a younger but more experienced professor. Gary was a good student and absorbed the lessons rapidly.

Discussions with students and experienced professors convinced Gary that a course outline with firm dates for exams and major assignments was absolutely necessary since students could not adjust their complicated schedules to accommodate last-minute changes. He was also advised to reduce the amount of material covered, which was easy initially but proved to be more difficult as additional cuts were needed. The process is ongoing.

Gary tried several presentation styles. Students complained that his handwriting was unreadable, so he tried class notes—but in addition to the construction being time consuming, they were boring and students either did not attend or went to sleep. He then tried notes with spaces for one-word answers, but the students viewed those as childish. He found that notes with large spaces for examples or derivations worked best, and they were easy to construct. He already had complete notes for lectures and created student notes by simply removing parts from them. This procedure allowed for more time for questions and stories, kept the students interested, and reduced the number of board errors.

As he became more experienced, Gary was able to write exams and projects that would challenge, but not overwhelm, the students. He scheduled exams at times that gave the students extra time, and he learned to recognize those problems that would be difficult to grade and used them only when it was educationally necessary. With more time available to him, Gary was able to get to know the TAs and the students better and found they were more like the students he remembered than he initially thought.

By taking a section of the computer laboratory in the statistics class, Gary learned what was giving the students trouble and was able to improve descriptions for the laboratory exercises. He also got to know the students in this small section very well and was able to recruit competent undergraduate TAs for the next offering of the course.

Today, Gary is teaching a large sophomore-junior class by himself, along with his cadre of selected graduate and undergraduate TAs. Although his grade distribution has not changed, his teaching evaluations have risen significantly and he has been able to put to rest his worry that firm grading would by punished by low evaluations. Both he and the students now agree that it is fun to go to class.

Gary has learned to be an “edutainer,” and the students are fascinated by the “war stories” he has built into his projects and exams. Since he better understands the pressures facing students, he is now better able to counsel them and give advice. Many of them realize that a letter of recommendation from someone with thirty years of industrial experience is an advantage and they make the effort to establish the one-on-one relationship Gary was looking for in the beginning. Although the large undergraduate course was Gary’s major challenge, he built such enthusiasm for his Risk Management elective course that enrollment had to be capped.

THE RESEARCH COMPONENT

Gary’s transition to the research environment was smoother than it was to the teaching component of his new career, although expectations and reality were, again, frequently in conflict. Professors were always willing to talk about their research interests provided Gary could track them down, but they were not actively looking for an “industrial perspective.” Gary soon learned that researchers were driven by the primeval need for survival—they needed funding for everything: graduate students, laboratory facilities, computers, release time, telephones, and even copying services. They needed to write proposals, give presentations, serve on committees, teach courses, supervise graduate students, etc. If they were successful, upper-level management in the university often rewarded them with administrative responsibilities.

Gary had no desire to compete in this environment. He simply wanted to work with some of the graduate students to pursue some ideas he felt compelled to develop. Professor Joe Pekny helped by involving Gary with his research group. In addition, he managed to bring in sufficient annual funding for a graduate student or two. This was ideal. He could conduct research, which resulted in publications and presentations while providing the necessary new material for his upper-level course in risk management. He also accepted a position as director for an industrial consortium that would channel funding into the department’s systems research efforts.

Gary developed an increasing appreciation for the stimulating nature of the academic environment. Working with professors from other universities and engineers from industry was stimulating, and he was able to develop lasting relationships with some of the students (easier with graduate students, however, than with undergraduates).
Gary had success in bringing an industrial perspective to the department and found it extremely rewarding to see former students who said they used his "stuff" in their jobs and found it valuable. Also, having the summer off for consulting and/or "down time" at the lake has been a bonus no industry is willing or able to match.

The challenges of academe are such that Gary, who was slightly bored in industry, now looks forward to every day. He has found that doing research and working with graduate students is exciting and has led to even more ideas for research. Since there is no textbook for the graduate-level course on risk analysis, Gary would like to write one...and there is always the challenge of getting everything right in teaching an undergraduate class!

**IMPROVING THE PROCESS**

There are a number of advantages for both the department and the students in having industrial professors on staff. For one thing, it is useful to maintain contact with industry to ensure that curriculum content is relevant. Other professional schools, such as medical and law schools, regularly have practitioners teach, and engineering colleges could benefit by following that lead and developing positions for professors with industrial experience. Industrial professors can help with the teaching load, particularly in design classes (although this was not the case with Gary). They tend to be more committed to teaching and are more likely to assign open-ended problems and projects that include teamwork and writing. Their presence can also help the department prepare students for industrial careers and thus satisfy ABET criterion 4. Professors who had active industrial research programs and contacts can help the department bring in more research contracts and ensure that the research is relevant.

The process can be improved, however. First, a critical mass of professors with extensive industrial experience is needed. One on staff is not enough—it is more appropriate if 20-30% of the faculty has extensive industrial experience.

Although tenure is probably not an issue for most returnees, planning for the next year is. A rolling contract that would allow the visiting professor to know at least a semester in advance whether or not he/she would still have a job would be helpful. (Although Gary’s position was originally viewed as a visiting position, the "visit" is now in its fifth year.) A title that implies a longer-term commitment (but without tenure) would be appropriate. In addition, a formal program would ease the red tape involved when the next engineer-in-residence is hired.

The department should ease the teaching transition of industrial professors and realize that they need to be taught how to teach—that they want to be taught how to teach. If there are no local workshops on teaching, the returnee should be encouraged to go to a national workshop such as the ASEE NETI (National Effective Teaching Workshop) at the annual meeting of ASEE. The department should provide a teaching mentor to discuss teaching with the returnee on a regular basis where both general pedagogical principles and the university’s specific rules can be explored. This mentor should invite the returnee to visit his/her classes and volunteer to visit the new professor’s classes. The mentor can be particularly helpful with grading and can provide resources such as a guide to teaching at that particular university. The returnee should be made aware of pedagogical journals such as *Chemical Engineering Education*, ASEE PRISM, the *Journal of Engineering Education* and appropriate books such as *Teaching Engineering* (available free at https://Engineering.Purdue.edu/ChE/Newsand_Events/publications/teaching_engineering).

These suggestions are also true for new assistant professors, most of whom want or are at least willing to be taught how to teach. Such teaching resources should also be made available to the experienced professors in the department who may want to "tune up" their teaching or learn some new tricks.

If the industrial professor is to be involved in research, the department should ease that transition. The returnee will usually be experienced in research, but the differences between academic and industrial approaches to research are likely to be surprising. Providing a research mentor who is in the same research area, but who is not the same person as the teaching mentor, is advisable. The mentor should carefully explain the need, and the mechanisms, for funding.

The returnee should collaborate with experienced professors on research and on proposals and should be encouraged to write proposals on his/her own—but the research mentor should review the proposal before it is sent out. The mentor should discuss the role of graduate students and undergraduates in research. The returnee should be told of the resources available at the university and of the formal and informal procedures for sharing those resources.

The department should prepare its faculty and staff for the arrival of the new professor, and the faculty should agree beforehand that hiring an industrial professor is a good idea. If the professors treat the individual with respect, the staff will also. The returnee’s office should be ready from the start and should be equivalent to the offices of other professors—"ready" means the office is clean, has furniture, the computer is hooked up to the network, the telephone is working, the nametag is on the door, secretarial assignments have been made, etc. Every new professor, whether industrial or not, should be introduced to everyone else in the department and should be invited to faculty meetings and other gatherings.

All new faculty, not just those from industry, can benefit from formal courses or workshops on pedagogy and from informal discussions with experienced teachers. They need mentoring in both research and teaching. Also, some industrial perspectives could be useful for universities—resource planning, for one, is a major push in industry but does not receive the same effort in academe. Risk analysis has proved...
valuable in industry and could be useful in academe (e.g., which centers should the university compete for?). Asking questions is valuable—how long do professors need for different tasks, what can be done to improve the process, if students aren’t the customers, who is, etc. Industrial faculty members can help ask the questions and help search for answers.

SUMMARY

Many chemical engineering departments have been criticized for a lack of industrial experience in their faculty. One approach to partially solving this problem is to hire early retirees from industry. As shown by the experiences related in this paper, these returning professors will probably experience some degree of cultural shock. Their transition to becoming productive contributors can be eased by providing both formal training in teaching and informal mentoring.

REFERENCES

1. Sacks, P., Generation X Goes to College, Open Court, Chicago, IL (1996)

Process Control Laboratory Experience

Continued from page 309.

The student provided written comments about the text and that no student provided written comments about the laboratory experience over the four-year period. Because there are no formal course evaluations for laboratory courses, student response data from the second-semester junior laboratory course concerning the laboratory course and this experiment is not available. Qualitative assessment of this experience based on comments received from the students during and after the experiment indicate that this experience has been generally well received by the students.

CONCLUSIONS

An introductory laboratory experience in process dynamics and control that is conducted concurrently with the process simulation and control course at Villanova University has been presented here. The experience is intended to reinforce the introductory concepts of dynamic simulation and feedback control presented in the classroom by using a simple liquid-level process. Based on quantitative and qualitative student responses in the laboratory and process simulation and control courses, the students found the experience a valuable addition to their process simulation and control education.

ACKNOWLEDGMENTS

A curriculum revision grant to the Villanova University Chemical Engineering Department from Air Products and Chemical Co. that supported development of this laboratory experience, and the contributions of Professor Robert Sweeney in the design and construction of the experimental system are gratefully acknowledged. I would also like to thank the Villanova University chemical engineering students over the past four years for their active participation in the continuing development and improvement of this experience, and Ami Badami and Jenny Papatoli of the class of 2003 for supplying their respective group’s experimental and simulation results that are presented in this paper.

REFERENCES

USING SPREADSHEETS AND VISUAL BASIC APPLICATIONS
As Teaching Aids for a Unit Operations Course

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The design of separation processes frequently uses intensive trial-and-error procedures as well as graphical methods such as McCabe-Thiele, Ponchon-Savarit, and Triangular diagrams. Using process simulation design packages such as ChemCAD, HYSYS, or AspenPLUS facilitates the design of complex processes, but students often treat simulators as black-boxes and tend to accept the results they obtain without further analysis. Additionally simulators may not provide the user with knowledge of all calculations that are performed or the respective algorithms. On the other hand, manual step-by-step calculations and graphical methods, while allowing students to understand the fundamentals of the design process, do not equip them with the ability to adapt software tools to the solution of chemical engineering problems or to critically use existing simulation packages. Tools such as MS Excel Macros and small Visual Basic Applications (VBA) bridge the gap between the previous alternatives.

At Tulane University, spreadsheets have been intensively used as teaching aids in undergraduate courses. Using spreadsheets and VBA to solve chemical engineering problems requires a deep understanding of the concepts behind the calculations, while the extensive and time-consuming trial-and-error procedures are left to the computer. The interactive nature of the spreadsheets and VBA programs allows "what if" analyses in which the parameter values are changed and the results are immediately displayed. One advantage of using spreadsheets as teaching tools is that the instructor can spend significantly more time discussing the fundamentals of mass transfer and the conceptual and quantitative description of processes, as well as the engineering insight that is needed in designing distillation, absorption, and other separations, by spending less class time on the details of solving problems graphically and by trial-and-error.

During this course, we initially lectured on the fundamentals of the calculation methods and presented illustrative examples. These first examples were solved using the trial-and-error and graphical procedures. Then we presented a solution to the same problem using spreadsheets and VBA. We discussed the details on how to program the spreadsheets and elaborate the macros. Once the students had learned how to use these tools, we asked them to develop their own Excel Macros and VBA programs to solve problems for homework. We used a process simulator (ChemCAD) during some of the lectures and compared results obtained from both approaches. As a final project, we asked the students to create a more complex algorithm for the design of an absorber. We were very pleased to see that the students had developed very creative, user-friendly computer programs. By the end of the course, 76% of the students used some kind of Excel spreadsheets and Macros to solve their homework, compared to 11.5% at the beginning of the semester.

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Kyriakos D. Papadopoulos is Professor of Chemical Engineering at Tulane University, having joined its faculty in 1981 and served as Department Chair from 1998 to 2001. He obtained his DEngSc from Columbia University in 1982. His research focuses on some of the phenomena that are important in the separation, transport, and reaction processes of particulate systems, with emphasis on drug delivery, lubricant technology, and environmental applications.

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It should be noted that although we have chosen Excel, Version 2000, for all examples in this paper, other spreadsheet programs such as Quattro Pro and Lotus will perform equally well.

DESIGN OF ABSORPTION COLUMNS

The design of absorption using the McCabe-Thiele diagram can be considered as a graphical solution to a series of sequential nonlinear equations. Spreadsheets have been used in solving simultaneous nonlinear equations due to their incorporation of a variety of mathematical functions and the ease of interactive programming, modification, and rapid graph generation.

Example 10.3 from Geankopolis is used here to illustrate the use of spreadsheets in the design of absorption units. The problem requires removal of acetone from an acetone-air gas stream using water in a countercurrent stage tower. The process schematic and spreadsheet used for solving this problem are shown in Figure 1. The initial data provided in the problem, such as the percentage of recovery and the flows and composition of the entering gas and liquid streams, are shown in the upper portion of the spreadsheet under design parameters. Assumptions include a constant molar overflow in the tower, negligible solubility of air in the water, and a phase equilibrium relationship that could be represented by Henry’s Law. The compositions of acetone in the liquid and vapor outlets, $x_N$ and $y_{N+1}$, can be obtained from a mass balance as shown in cells D8 and D9 of the spreadsheet; the equations have been added to the respective comment bubbles on the graph.

The equilibrium and operating lines are plotted using Henry’s Law and Equation 10.3-13 from Geankopolis, as shown in the D15-E25 cell range of the spreadsheet and the respective comment bubbles. Using Excel’s “chart wizard,” an X-Y plot can be readily constructed showing the equilibrium and operating lines.

### Absorption of Acetone in a Countercurrent Stage Tower

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<th>Design Parameters</th>
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<tbody>
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<td>% Recovery</td>
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<tr>
<td>L [kg-mol/h]</td>
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<tr>
<td>V [kg mol-h]</td>
</tr>
<tr>
<td>x0, yN+1</td>
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### Calculating the Operating and Equilibrium Line

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### Calculating the Concentration of Acetone Plate by Plate

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</table>

Figure 1. Spreadsheet used for illustrating absorption of acetone in a countercurrent stage tower.
The next step involves the plate-by-plate calculation of the concentration of acetone in the liquid and vapor phases. In hand calculations, this step is made graphically, but in this case advantage is taken of the fact that both the operating and equilibrium lines are expressed as mathematical functions, so the concentration in the liquid and vapor phases can be easily determined numerically, as shown in the D29-F42 cell range of the spreadsheet. The \((x,y)\) data series is added to the existing graph, thus completing a numerical McCabe-Thiele diagram, also shown in Figure 1.

Finally, the number of ideal stages required for the desired percentage of recovery is determined using the built-in "FORECAST" function, which operates as a linear interpolator. The series in the interpolation represents the number of stages and the concentration of the vapor phase (columns starting at F29 and G29), while the value to be interpolated is the calculated concentration at the exit of the tower (E7).

Once the spreadsheet is built, several "what-if" scenarios can be analyzed. For instance, in this example an increase in the recovery requirement as well as a moderate increase in the gas flow will readily show that the number of stages required will increase significantly. Also, a large decrease in the liquid flow rate or an increase in the gas flow rate will demonstrate that the separation is impossible to achieve as the operating line and the equilibrium line cross each other.

**INTERFACIAL COMPOSITIONS IN MASS TRANSPORT BETWEEN TWO PHASES**

Trial-and-error iterative procedures for determining the composition of the interface between immiscible phases are frequently required in mass-transfer-based separation processes. To demonstrate the versatility of spreadsheets in accomplishing this task, we use Example 10.4-1 from Geankoplis, as shown in Figure 2. The objective of this problem is to determine the interfacial concentrations of the vapor and liquid phases \(y_Ai\) and \(x_{Ai}\) respectively, in a wetted-

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**Figure 2.** Spreadsheet and Macro used for interative calculation of interface compositions in interphase mass transfer.
The first step in solving this problem involves initial guesses for \( x_{Ai} \) and \( y_{Ai} \). In solving the problem by hand, these guesses are crucial to the rapid convergence of the iterative process. Spreadsheets are less sensitive to the initial guesses as a large number of iterations can be processed and visualized in fractions of seconds.

In Figure 2, cells D13-D19 display the equations and columns E - H display results from four iterations. Once the initial guesses are selected (cells E11 and E12), the slope for the line connecting the bulk concentration and the assumed interfacial concentrations is calculated, as shown in cell E16. With the slope from E15 and point P (the bulk concentration in cells D6 and D7) on the \( x-y \) plot in the lower-right corner of Figure 2, an equation for a straight line is deduced as shown in cell D17. A third-order polynomial was used to fit the equilibrium data (cell D18).

The Excel function “SOLVER” is used to solve simultaneously the equations in cells D17 and D18 by minimizing the error between the values of cells E16 and E17. SOLVER can use a Newton or a conjugate numerical procedure to find the answer; the default Newton procedure was chosen for this example. When comparison between the values for \( x_{Ai} \) and \( y_{Ai} \) from this procedure (cells E15 and E16) and the initial guesses (cells E12 and E13) shows a discrepancy, an additional iteration is required. The latest calculated values for \( x_{Ai} \) and \( y_{Ai} \) (cells E15 and E16) are used as the new initial guesses.

Due to the ease of modification of spreadsheets, the cells containing the equations can be copied and pasted into the next columns as many times as necessary. In this example, four iterations provide a reliable answer (less than 0.1% between the latest and penultimate calculated values).

What-if” scenarios in this example include how an increase in the liquid-film mass-transfer coefficient will readily show that the value for the interfacial concentrations \( x_{Ai} \) and \( y_{Ai} \) increase and how a large decrease in the bulk concentration will produce a significant decrease in \( x_{Ai} \) and \( y_{Ai} \). In order to automate the iteration process, a MACRO was created using

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Figure 3. Spreadsheet and Macro used for distillation of a benzene-toluene mixture.
DISTILLATION

While interfacial composition calculations used a VBA program and the absorption example was based on cell and formula manipulation of the spreadsheet, in this example a combination of both approaches is used for the design of a distillation unit. Such design is made using the McCabe-Thiele diagram with special considerations for the location of the feed and the types of condenser and reboiler.[6]

Example 11.4-2 from Geankoplis’ book is chosen to illustrate use of spreadsheets in the design of distillation towers. The problem requires the rectification of a benzene-toluene mixture. Initial data of the problem include the flow and condition of the feed stream as well as its composition. The reflux ratio and the compositions of the distillate and bottoms are also specified. These design parameters are located in the upper portion of Figure 3 under design parameters. It is assumed that a constant molar overflow is present in the tower.

Solving the overall mass balance (cell F15) and a benzene mass balance (cell F16) simultaneously with SOLVER provides the values for the distillate and bottom-stream flow-rates (cells C15 and C16). In this example, we take advantage of the capabilities of SLOVER for multivariable calculations. The error cell (cell F17) is set as the target cell, and the SOLVER should change the values of cells C15 and C16 until the value of F16 becomes negligible. The multivariable optimization capabilities of SLOVER are implicit, which is very useful since no additional programming is required.

After calculating all flow-rates, the next step is to build the equilibrium and operating lines. The equilibrium line is constructed using experimental equilibrium data and fitted to a fifth-degree polynomial using the TRENDLINE option of Excel. The “q line” is calculated by using a boiling point diagram and the physical properties of the feed stream. Cells B18 to D21 show the calculations performed to obtain the value of q and hence the slope and intercept of the “q line.” The enriching line is constructed using Eq. 11.4-8 from Geankoplis,[6] as shown in cell range B26 to D27. Once the slope and intercept of the q and enriching lines are determined, a numerical method is used to calculate the intercept between these two lines. SLOVER is again used as shown in cell range E21 to G25. Since this problem requires the use of SLOVER twice, a VBA program is built and assigned to a button so these calculations are automated with a single click by the user. The stripping line is constructed using the initial conditions of the problem and the intercept between the q and the enriching lines as shown in cell range B28 to D30.

The table containing the data as well as the formulas used to determine the equilibrium, enriching, stripping, and q lines is shown on cell range B32 to G38. To calculate the number of plates required for the rectification, the following procedure is followed, as shown in cell range B40 to F50. The initial point (cell B42) corresponds to the bottoms concentration, x_{w, Eq}, is calculated using the equilibrium equation (cell C42), and the equations for the enriching and stripping lines are used for cells D42 to E50. For every iteration an IF statement is used to select the larger value for x. This IF statement initially selects the stripping line as the operating line, but once the “q line” is reached, the enriching line becomes the operating line. The number of plates is calculated using the FORECAST function as shown in cells E29 to G29. Based on the spreadsheet, “what-if” scenarios can be considered and the student is able to visualize the effect of changes in the design parameters such as concentrations, flow-rates, reflux ratios, etc., on the number of plates required for a desired separation. Concepts such as the pinch point and the minimum reflux ratio can also be analyzed.

CONCLUSIONS

MS Excel Macros and Visual Basic for Applications enhanced the educational experience of students in a junior-level separation processes course, teaching them to develop simple software and providing them with an intermediate step between doing hand calculations and using commercially available packages. Distillation, absorption, and interfacial mass-transfer problems were solved using spreadsheets and were incorporated into a web-based learning platform.

In addition to analyzing several “what-if” scenarios, these teaching tools can also be slightly modified to solve the inverse problems. For example, in the absorption case, the number of stages as well as the inlet flow-rates and concentrations can be given as design parameters, and then the students can be asked to determine the concentration of the outlet streams. Also, in the distillation case, the number of plates in the enriching and stripping sections can be fixed, and the students can be asked to determine the appropriate reflux ratio and inlet flow-rates to achieve a certain degree of purity in the top or bottom streams.

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Ahmet N. Palazoglu, Professor • Ph.D., Rensselaer Polytechnic Institute, 1984 • Process control and process monitoring
Ronald J. Phillips, Professor • Ph.D., Massachusetts Institute of Technology, 1989 • Transport processes in biomembranes, Newtonian and non-Newtonian suspension mechanics
Robert L. Powell, Professor and Chair • Ph.D., Johns Hopkins University, 1978 • Rheology, suspension mechanics, magnetic resonance imaging of suspensions
Subhash H. Richards, Professor • Ph.D., University of California, Berkeley, 1976 • Semiconductor quantum dots, high Tc superconducting ceramics, polymer composites for optics
Dewy D.Y. Ryu, Professor • Ph.D., Massachusetts Institute of Technology, 1967 • Biomolecular process engineering and recombinant bioprocess technology
Julie M. Schoenung, Associate Professor • Ph.D., Massachusetts Institute of Technology, 1987 • Materials systems analysis, pollution prevention and waste minimization, process economics
James F. Shackelford, Professor • Ph.D., University of California, Berkeley, 1971 • Structure of materials, biomaterials, nondestructive testing of engineering materials
J.M. Smith, Professor Emeritus • Sc.D., Massachusetts Institute of Technology, 1943 • Chemical kinetics and reactor design
Pieter Stave, Professor • Sc.D., Massachusetts Institute of Technology, 1973 • Membrane separations, self-assembly, colloid and surface science, nanotechnology, surface modification, biotechnology
Stephen Whitaker, Associate Professor • Ph.D., University of Delaware, 1959 • Multiphase transport phenomena

Department of Chemical Engineering & Materials Science

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Steven C. George (University of Washington)
Stanley B. Grant (California Institute of Technology)
Juan Hong (Purdue University)
Enrique J. Lavernia (Massachusetts Institute of Technology)
Henry C. Lim (Northwestern University)
Jia Grace Lu (Harvard University)
Martha L. Mecartney (Stanford University)
Farghalli A. Mohamed (University of California, Berkeley)
Daniel R. Mumm (Northwestern University)
Andrew J. utnam (University of Michigan)
Frank G. Shi (California Institute of Technology)
Vasan Venugopalan (Massachusetts Institute of Technology)

Joint Appointments:
G. Wesley Hatfield (Purdue University)
Noo Li Jeon (University of Illinois)
Sunny Jiang (University of South Florida)
Roger H. Rangel (University of California, Berkeley)
William A. Sirignano (Princeton University)

Adjunct Professors
Russell Chou (Carnegie Mellon University)
Andrew Shapiro (University of California, Irvine)
Victoria Tellkamp (University of California, Irvine)

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- Molecular and Cellular Bioengineering
- Process Systems Engineering (Design, Optimization, Dynamics, and Control)
- Semiconductor Manufacturing

GENERAL THEMES

- Energy and the Environment
- Nanoelectronics

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J. P. Chang
(William F. Seyer Chair in Materials Electrochemistry)

P. D. Christofides

Y. Cohen

J. Davis
(Vice Chancellor for Information Technology)

S. K. Friedlander
(Parsons Professor of Chemical Engineering)

R. F. Hicks

L. Ignarro
(Nobel Laureate)

E. L. Knuth
(Professor Emeritus)

J. C. Liao

V. Manousiouthakis

H. G. Monbouquette

K. Nobe

G. Orkoulas

L. B. Robinson
(Professor Emeritus)

S. M. Senkan

Y. Tang

W. D. Van Vorst
(Professor Emeritus)

V. L. Weller
(Professor Emeritus)

A.R. Wazzan
(Dean Emeritus)

CONTACT

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Graduate Advisor
Department of Chemical/ Environmental Engineering, University of California
Riverside, CA 92521

FACULTY
- Wilfred Chen, Caltech
- David R. Cocker, Caltech
- Marc A. Deshusses, ETH, Zurich
- Robert C. Haddon, Penn State
- Eric M.V. Hoek, Yale
- Mark R. Matsumoto, UC Davis
- Dimitrios Morikis, Northeastern
- Ashok Mulchandani, McGill
- Nosang V. Myung, UCLA
- Joseph M. Norbeck, Nebraska
- Mihri Ozkan, UC San Diego
- Jianzhong Wu, UC Berkeley
- Yushan Yan, Caltech
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Frances H. Arnold Anand R. Asthagiri John F. Brady Mark E. Davis Richard C. Flagan
George R. Gavalas (Emeritus) Konstantinos P. Giapis Sossina M. Haile Julia A. Kornfield
John H. Seinfeld Christina D. Smolke David A. Tirrell Nicholas W. Tschoegl (Emeritus) Zhen-Gang Wang

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- Self Assembly Chemistry

Faculty
- John Angus
- Harihara Baskaran
- Robert Edwards
- Donald Feke
- Daniel Lacks
- Uziel Landau
- Chung-Chiun Liu
- J. Adin Mann
- Heidi Martin
- Peter Pintauro
- Syed Qutubuddin
- Robert Savinell
- Thomas Zawodzinski

For more information on Graduate Research, Admission, and Financial Aid, contact:

Graduate Coordinator
Department of Chemical Engineering
E-mail: grad@cheme.cwru.edu
Web: http://www.cwru.edu/cse/eche

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Joel Fried
Rakesh Govind
Vadim Guliants
Daniel Hershey
Chia-chi Ho
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Yuen-Koh Kao
Soon-Jai Khang
William Krantz
Jerry Y. S. Lin
Neville Pinto
Peter Smirniotis

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Director, Graduate Studies
Department Chemical and Materials Engineering
PO Box 210171
University of Cincinnati
Cincinnati, Ohio 45221-0171
E-mail: deena.good@uc.edu or ykao@alpha.che.uc.edu

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Polymers
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FACULTY RESEARCH:

"Andreas Acrivos*: Rheology of concentrated suspensions; Dielectrophoresis in flowing suspensions; Dynamical systems theory and chaotic particle motions

Alexander Couzis: Polymorph selective templated crystallization; Moleculary thin organic barrier layers; Surfactant facilitated wetting of hydrophobic surfaces; soft materials

"Morton Denn*: Polymer science and rheology; non-Newtonian fluid mechanics

Lane Glickstein: Bioengineering with cellular materials; Spectroscopy-guided molecular engineering; Structural studies of self-assembling proteins; Bioprocessing

Robert Graff: Coal liquefaction; Pollution prevention; Remediation

Leslie Isaacs: Preparation and characterization of novel optical materials; Recycling of pavement materials; Application of thermo-analytic techniques in materials research

Jae Lee: Theory of reactive distillation; Process design and control; Separations; Bioprocessing

"Charles Maldarelli: Interfacial fluid mechanics and stability; Surface tension driven flows and microfluidic applications; Surfactant adsorption, phase behavior and nanostructuring at interfaces

Irben Rinard: Process design methodology; Dynamic process simulation; Micro-reaction technology; Process control; Bioprocessing

David Rumschitzki: Transport and reaction aspects of arterial disease; Interfacial fluid mechanics and stability; Catalyst deactivation and reaction engineering

Renel Shinnar*: Advanced process design methods; Chemical reactor control; Spinodal decomposition of binary solvent mixtures; Process economics; Energy and environment systems

Carol Steiner: Polymer solutions and hydrogels; Soft biomaterials, Controlled release technology

Gabriel Tardos: Powder technology; Granulation; Fluid particle systems, Electrostatic effects; Air pollution

Sheldon Weinbaum*: Fluid mechanics, Biotransport in living tissue; Modeling of cellular mechanism of bone growth; bioheat transfer; kidney function

Herbert Weinstein: Fluidization and multiphase flows: multiphase chemical reactor analysis and design, Multiphase reactor analysis and design

ASSOCIATED FACULTY:

"Jimmy Feng: (Mechanical Engr.) Liquid crystals

"Joel Koplik: (Physics) Fluid mechanics; Molecular modeling: Transport in random media

"Hernan Makse: (Physics) Granular mechanics

"Mark Shaltout: (Physics) Experimental granular rheology; Computational granular fluid dynamics; Experimental spatio-temporal control of patterns

* Levich Institute
* National Academy of Sciences
= National Academy of Engineering
= American Academy of Arts and Sciences

CONTACT INFORMATION:

Department of Chemical Engineering
City College of New York
Convent Avenue at 140th Street
New York, NY 10031
www.che.engr.ccny.cuny.edu
che.hr@aol.com
CSU Faculty
A. Annapragada (University of Michigan)
J.M. Belovich (University of Michigan)
G. Chatzimavroudis (Georgia Institute of Technology)
G.A. Coullman (Case Western Reserve University)
J.E. Gatica (State University of New York at Buffalo)
B. Ghorashi (Ohio State University)
E.S. Godleski (Cornell University)
R. Lustig (Institute of Thermo- and Fluidynamics of the Ruhr-University Bochum, Germany)
D.B. Shah (Michigan State University)
O. Tatu (Arizona State University)
S.N. Tewari (Purdue University)
S. Ungarala (Michigan Technological University)

CCF Collaborating Faculty
J. Arendt (Ohio State University)
B. Davis (Pennsylvania State University)
K. Derwin (University of Michigan)
A. Fleischman (Case Western Reserve University)
B. Gopakumaram (Ohio State University)
M. Grabiner (University of Illinois)
S. Halliburton (Vanderbilt University)
C. McDevitt (University of London, U.K.)
C. McMillin (Case Western Reserve University)
A. Ramanurthi (Oklahoma State University)
S. Roy (Case Western Reserve University)
R. Setser (Washington University)
R. Shekhar (Ohio State University)
W. Smith (Cleveland State University)
A. van den Bogert (University of Utrecht, The Netherlands)
I. Vesely (University of Western Ontario, Canada)
P. Stephen Williams (University of Wales, U.K.)
G. Yue (University of Iowa)

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D. Eng. Chemical Engineering

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For more information, write to:
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Department of Chemical and Biomedical Engineering
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**Department of Chemical and Biological Engineering**

**Faculty and Research Interests**

<table>
<thead>
<tr>
<th>Kristi S. Anseth</th>
<th>Polymers, Biomaterials, Tissue Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Christopher N. Bowman</td>
<td>Polymers, Membrane Materials</td>
</tr>
<tr>
<td>David E. Clough</td>
<td>Process Control, Applied Statistics</td>
</tr>
<tr>
<td>Robert H. Davis</td>
<td>Fluid Mechanics, Biotechnology, Membranes</td>
</tr>
<tr>
<td>John L. Falconer</td>
<td>Catalysis, Zeolite Membranes</td>
</tr>
<tr>
<td>R. Igor Gamow</td>
<td>Biophysics, High Altitude Physiology, Human Performance, Diving Physiology</td>
</tr>
<tr>
<td>Steven M. George</td>
<td>Surface Chemistry, Thin Films, Nanoengineering</td>
</tr>
<tr>
<td>Doug Gin</td>
<td>Polymers</td>
</tr>
<tr>
<td>Ryan Gill</td>
<td>Biotechnology</td>
</tr>
<tr>
<td>Christine M. Hrenya</td>
<td>Fluidization, Granular Systems, Fluid Mechanics</td>
</tr>
<tr>
<td>Dhinakar S. Kompala</td>
<td>Biotechnology, Animal Cell Cultures, Metabolic Engineering</td>
</tr>
<tr>
<td>J. Will Medlin</td>
<td>Heterogeneous Catalysis, Solid-State Sensors, Computational Chemistry</td>
</tr>
<tr>
<td>Richard D. Noble</td>
<td>Membranes, Separations</td>
</tr>
<tr>
<td>W. Fred Ramirez</td>
<td>Process Control, Biotechnology</td>
</tr>
<tr>
<td>Theodore W. Randolph</td>
<td>Biotechnology, Supercritical Fluids</td>
</tr>
<tr>
<td>Robert L. Sani</td>
<td>Transport Phenomena, Applied Mathematics</td>
</tr>
<tr>
<td>Daniel K. Schwartz</td>
<td>Interfacial and Colloid Science</td>
</tr>
<tr>
<td>Alan W. Weimer</td>
<td>Ceramics, Energy, Reaction Engineering</td>
</tr>
</tbody>
</table>

Graduate students may participate in the interdisciplinary Biotechnology Training Program and the interdisciplinary NSF Industry/University Cooperative Research Center for Membrane Applied Science and Technology and the Center for Fundamentals and Applications of Photopolymerizations.

For information and application
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- Organic and inorganic membranes (Way, Baldwin)
- Polymeric materials (Dorgan, McCabe, Wu)
- Colloids and complex fluids (Marr, Wu)
- Electronic materials (Wolden)
- Fuel cell membranes (Way)

Theoretical and Applied Thermodynamics
- Natural gas hydrates (Sloan)
- Molecular simulation and modelling (Ely, McCabe)

Transport Properties and Processes
- Dermal absorption (Bunge)
- Microfluidics (Marr)

Space and Microgravity Research
- Membranes on Mars (Way, Baldwin)
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Rice University (Joint Appointment)
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Biofilm Processes, Biomaterials

Ranjan Srivastava, Ph.D.,
University of Maryland
Experimental and Computational
Biology, Biomolecular Network Analysis,
Stochastic Biological Phenomena,
Evolutionary Kinetics

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North Carolina State University
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Bioremediation with Genetically-
Engineered Bacteria, Enzymatic Green
Chemistry, Biochemical Engineering,
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Electronic Materials, Energy Systems,
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Massachusetts Institute of Technology
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Materials Synthesis and Characterization,
Combustion

POLYMER SCIENCE

Patrick T. Mather, Ph.D.,
University of California, Santa Barbara
Polymers, Microstructure and
Rheology, Liquid Crystalinity,
Inorganic-Organic Hybrids

Richard Parnas, Ph.D.,
University of California, Los Angeles
Composites, Biomaterials

Montgomery T. Shaw, Ph.D.,
Princeton University
Polymer Rheology and Processing,
Polymer-Solution Thermodynamics

Robert A. Weiss, Ph.D.,
University of Massachusetts
Polymer Structure-Property Relationships,
Ion-Containing and Liquid Crystal
Polymers, Polymer Blends

Lei Zhu, Ph.D., University of Akron
Polymer Phase Transitions, Structures
of Block Copolymers, Polymeric
Nanocomposites, Biodegradable Block
Copolymers for Drug Delivery

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C.O. Bennett, J.P. Bell, A.T. DiBenedetto,
G.M. Howard, R.W. Coughlin, M.B. Cutlip

COMPUTER APPLICATIONS

Luke E. K. Achenie, Ph.D.,
Carnegie Mellon University
Modeling and Optimization,
Molecular Design, Artificial
Intelligence, Flexibility Analysis

Thomas F. Anderson, Ph.D.,
University of California at Berkeley
Modeling of Separation Processes,
Fluid-Phase Equilibria

Douglas J. Cooper, Ph.D.,
University of Colorado
Process Modeling, Monitoring and Control

Suzanne Schadel Fenton, Ph.D.,
University of Illinois, Urbana-Champaign
Computational Fluid Dynamics,
Turbulence, Two-Phase Flow

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For further information, write:

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- Environmental science and engineering
- Fluid mechanics
- Materials science and engineering
- Process design and evaluation

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Faculty & Research Areas

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Research Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ian Baker</td>
<td>(Oxford)</td>
<td>Structure/property relationships of materials, electron microscopy</td>
</tr>
<tr>
<td>John Collier</td>
<td>(Dartmouth)</td>
<td>Orthopaedic prostheses, implant/host interfaces</td>
</tr>
<tr>
<td>Alvin Converse</td>
<td>(Delaware)</td>
<td>Kinetics &amp; reactor design, enzymatic hydrolysis of cellulose</td>
</tr>
<tr>
<td>Benoit Cushman-Roisin</td>
<td>(Florida State)</td>
<td>Numerical modeling of environmental fluid dynamics</td>
</tr>
<tr>
<td>Harold Frost</td>
<td>(Harvard)</td>
<td>Microstructural evolution, deformation, and fracture of materials</td>
</tr>
<tr>
<td>Tillman Gerngross</td>
<td>(Technical University of Vienna)</td>
<td>Engineering of glycoproteins, fermentation technology</td>
</tr>
<tr>
<td>Ursula Gibson</td>
<td>(Cornell)</td>
<td>Thin film deposition, optical materials</td>
</tr>
<tr>
<td>Francis Kennedy</td>
<td>(RPI)</td>
<td>Tribology, surface mechanics</td>
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<tr>
<td>Daniel R. Lynch</td>
<td>(Princeton)</td>
<td>Computational methods, oceanography, and water resources</td>
</tr>
<tr>
<td>Lee Lynd</td>
<td>(Dartmouth)</td>
<td>Biomass processing, pathway engineering, reactor &amp; process design</td>
</tr>
<tr>
<td>Victor Petrenko</td>
<td>(USSR Academy of Science)</td>
<td>Physical chemistry of ice</td>
</tr>
<tr>
<td>Horst Richter</td>
<td>(Stuttgart)</td>
<td>Thermodynamics, multiphase flow, energy conversion, process design</td>
</tr>
<tr>
<td>Erland Schulson</td>
<td>(British Columbia)</td>
<td>Physical metallurgy of metals and alloys</td>
</tr>
<tr>
<td>Charles E. Wyman</td>
<td>(Princeton)</td>
<td>Biomass pretreatment &amp; hydrolysis, cellulase synthesis &amp; kinetics, process design</td>
</tr>
</tbody>
</table>

For further information, please contact:

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<table>
<thead>
<tr>
<th>Faculty Name</th>
<th>Title</th>
<th>Research Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>N. R. Amundson (Cullen Professor)</td>
<td>Chemical Reactions; Transport; Mathematical modeling</td>
<td></td>
</tr>
<tr>
<td>V. Balakotaiah (John &amp; Rebecca Moores Professor)</td>
<td>Chemical Reaction Engineering; Applied mathematics</td>
<td></td>
</tr>
<tr>
<td>A. T. Capitano (Assistant Professor)</td>
<td>Tissue Engineering; In Vitro Toxicology</td>
<td></td>
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<tr>
<td>V. M. Donnelly (Professor)</td>
<td>Plasma Processing; Electronic Materials</td>
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<tr>
<td>C. Ehlig-Economides (Professor)</td>
<td>Petroleum Engineering; Simulating Reservoir Flow Behavior</td>
<td></td>
</tr>
<tr>
<td>M. J. Economides (Professor)</td>
<td>Petroleum Engineering; Energy</td>
<td></td>
</tr>
<tr>
<td>D. J. Economou (John &amp; Rebecca Moores Professor)</td>
<td>Electronic Materials; Composites and ceramics</td>
<td></td>
</tr>
<tr>
<td>M. P. Harold (Dow Professor, Chairman)</td>
<td>Chemical Reaction Systems</td>
<td></td>
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<tr>
<td>E. J. Henley (Emeritus Professor)</td>
<td>Reliability Engineering; Biomedical engineering</td>
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<tr>
<td>R. Krishnamoorti (Associate Professor)</td>
<td>Polymeric Materials; Biomaterials</td>
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<tr>
<td>D. Luss (Cullen Professor)</td>
<td>Chemical Reaction Engineering</td>
<td></td>
</tr>
<tr>
<td>K. K. Mohanty (Professor)</td>
<td>Fluid flow in porous media; Biomaterials</td>
<td></td>
</tr>
<tr>
<td>M. Nikolaou (Associate Professor)</td>
<td>Computer-aided process engineering</td>
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<tr>
<td>J. T. Richardson (Professor)</td>
<td>Catalysis &amp; reaction engineering</td>
<td></td>
</tr>
<tr>
<td>F. M. Tiller (Emeritus Professor)</td>
<td>Fluid/particle separation</td>
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<tr>
<td>P. Vekilov (Associate Professor)</td>
<td>Protein crystallization &amp; Phase transitions</td>
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</tr>
<tr>
<td>R. C. Willson (Associate Professor)</td>
<td>Biomolecular Recognition; Environmental biotechnology</td>
<td></td>
</tr>
</tbody>
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Mobolaji E. Aluko, Professor
PhD, University of California, Santa Barbara
Reactor modeling • crystallization • microelectronic and ceramic materials processing • process control • reaction engineering analysis

Joseph N. Cannon, Professor • PhD, University of Colorado
Transport phenomena in environmental systems • computational fluid mechanics • heat transfer

Ramesh C. Chawla, Professor • PhD, Wayne State University
Mass transfer and kinetics in environmental systems • bioremediation • incineration • air and water pollution control

William E. Collins, Associate Professor • PhD, University of Wisconsin-Madison
Polymer deformation, rheology, and surface science • biomaterials • bioseparations • materials science

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L.J. Thibodeaux (Ph.D., Louisiana State University)
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K.E. Thompson (Ph.D., University of Michigan)
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K.T. Valsaraj (Ph.D., Vanderbilt University)
Environmental Transport, Separations

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Combustion, Heterogeneous Reactions

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F.F. Farshad, PhD, University of Oklahoma, OK (1975)
J.D. Garber (Head), PhD, Georgia Institute of Technology, GA (1971)
A.G. Hill, PhD, Louisiana Technical University, LA (1980)
B.L. Newman, PhD, University of Virginia, VA (1988)
A.B. Ponter, DSc, Birmingham University, UK (1986) PhD, Manchester (1966)
J.R. Reinhardt, PhD, University of Arkansas, AR (1977)

Research Centers

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Center for Metals, Polymers and Composites Research • Dr. R.D.K. Misra, Director

Research Areas

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  Deformation Behavior of Polymers and Composites
  Formability and Fracture Toughness of High-Strength Steels
  Cold Work Embrittlement of Interstitial-Free Steels
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  Liquid Spreading
  Multiphase Flow
  Surface Roughness

• Thermodynamics and Process Engineering
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  Chemical Reactor Design, Stability and Dynamics
  Process Simulation and Design

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Chemical Engineering Department
Manhattan College
Riverdale, NY 10471

chmldept@manhattan.edu
http://www.engineering.manhattan.edu
Faculty and Research Areas

Raymond A. Adomaitis (IIT) • Systems modeling and simulation methodologies; semiconductor manufacturing
Mikhail A. Anisimov (Moscow) • Critical phenomena and phase transitions in fluids and fluid mixtures
Timothy A. Barbari (Texas-Austin) • Membrane science, polymer science, biomaterials
William E. Bentley (Colorado) • Biochemical/metabolic engineering, applications of molecular biology
Richard V. Calabrese (Massachusetts) • Multiphase flow, turbulence and mixing
Kyu Yong Choi (Wisconsin) • Polymer reaction engineering
Panagiotis Dimitrakopoulos (Illinois-Urbana) • Biofluid mechanics, biophysics and microrheology
Sheryl H. Ehrman (UCLA) • Aerosol and nanoparticle technology
John P. Fisher (Rice) • Tissue engineering, biomaterials
James W. Gentry (Texas-Austin) • Aerosol science and engineering
Sandra C. Greer (Chicago) • Physical chemistry, polymer science, biomacromolecules, phase equilibria
Maria I. Klapa (MIT) • Metabolic engineering, bioinformatics, modeling of biological networks
Peter Kofinas (MIT) • Polymer science and engineering
Thomas J. McAvoy (Princeton) • Process control, fault detection
Tracey R. Pulliam Holoman (Maryland) • Biochemical engineering and bioremediation
Jan V. Sengers (U. Amsterdam) • Critical phenomena, thermophysical properties of fluids and fluid mixtures
Srinivasa R. Raghavan (N.C. State) • Polymers, colloids, complex fluids, self-assembly
Nam Sun Wang (Caltech) • Biochemical engineering
William A. Weigand (IIT) • Biochemical engineering, bioprocess control and optimization
Evangelos Zafiriou (Caltech) • Process control, identification and optimization

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**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

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**FACULTY**

**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

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

**A. R. MOREIRA, Ph.D.**  
*Pennsylvania*  
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**G. F. PAYNE, Ph.D.*  
*Michigan*  
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**G. RAO, Ph.D.**  
*Drexel*  
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<thead>
<tr>
<th>Area</th>
<th>Research Focus</th>
<th>Faculty Members</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Biomaterials</strong></td>
<td>Tissue engineering, biomedical engineering, blood-material interactions</td>
<td>J.L. Brash, K. Jones, H. Sheardown,</td>
</tr>
<tr>
<td><strong>Bioprocessing</strong></td>
<td>Membranes, environmental engineering, bioseparation, fermentation, recombinant proteins</td>
<td>L. Crossley, C. Filipe, R. Ghosh,</td>
</tr>
<tr>
<td><strong>Transport Phenomena</strong></td>
<td>Heat transfer, experimental &amp; computational fluid mechanics, membranes</td>
<td>J. Dickson, A. N. Hrymak, P.E. Wood</td>
</tr>
<tr>
<td><strong>Polymer Science</strong></td>
<td>Pulp &amp; paper science, polymerization, polymer characterization, synthesis</td>
<td>A. E. Hamielec (Emeritus), R. H. Pelton, S. Zhu, K. Kostanski (Adjunct)</td>
</tr>
<tr>
<td><strong>Polymer Engineering</strong></td>
<td>Polymer processing, rheology, CAD/CAM methods, extrusion</td>
<td>A. E. Hamielec (Emeritus), A. N. Hrymak, M. Thompson, J. Viachopoulos, S. Zhu</td>
</tr>
<tr>
<td><strong>Process Systems Engineering</strong></td>
<td>Multivariate statistical methods, computer process control, optimization</td>
<td>J. F. MacGregor, T. E. Martin, Y. Samyudia, C. L. E. Swartz, P. Taylor, T. Kourt (Adjunct)</td>
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Department of Chemical Engineering  
McMaster University  
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CANADA

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Fax: 905-521-1350  
Email: chemeng@mcmaster.ca  
Http://www.chemeng.mcmaster.ca
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C. Barry Carter
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Molecular materials and interfaces, organic semiconductors, molecular electronics, atomic force microscopy

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Wei-Shou Hu
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Yianis Kaznessis
Computer modeling of biological systems, structural bioinformatics, molecular recognition phenomena

Efrosini Kokkoli
Targeted drug delivery

Satish Kumar
Transport and interfacial phenomena, complex materials, nanofluids and microfluidics

Chris Leighton
Magnetic and electronic properties of thin film magnetic materials and heterostructures

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Christopher W. Macosko
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Jennifer Maynard
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Corrosion, thermodynamics of solids, low-energy nuclear reactions

Christopher Palmström
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Fluid mechanics and rheology, colloid and interface science, transport reaction and stress phenomena, materials processing; coatings

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Michael Tsapatsis
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Online Application: http://www.umr.edu/~cisapps/gradappd.html

Neil L. Book
Associate Professor, Ph.D. Colorado

Daniel Forciniti
Associate Professor, Ph.D. North Carolina State
Bioseparations, Thermodynamics, Statistical Mechanics

A.I. Liapis
Professor, Ph.D. ETH-Zurich

Douglas K. Ludlow
Professor and Chair, Ph.D. Arizona State
Surface Characterization of Adsorbents and Catalysts, Applications of Fractal Geometry to Surface Morphology

Nicholas C. Morosoff
Professor Emeritus, Ph.D. Brooklyn Polytech
Plasma Polymerization, Membranes

Parthasakha Neoghi
Professor, Ph.D. Carnegie-Mellon
Interfacial Phenomena, Drug Delivery

X B Reed, Jr.
Professor Emeritus, Ph.D. Minnesota
Fluid Mechanics, Transport Phenomena and Chemical Reaction Engineering, Including those of Particles, Drops, and Bubbles, Large-Scale Structure of Shear Turbulence, and Impact of Fine-Scale Structure on Chemical Reactions

Y.T. Shah
Professor and Provost, Ph.D. MIT
Chemical Reaction and Reactor Engineering

Oliver C. Sitton
Associate Professor, Ph.D. Missouri-Rolla
Bioengineering

Jee-Ching Wang
Assistant Professor, Ph.D. Penn State
Molecular Simulations of Transport in Confined Systems, Molecular Simulations of Surfactant Systems, Molecular Properties of Materials

Yangchuan Xing
Assistant Professor, Ph.D. Yale
Synthesis, Processing, and Characterization of Nanomaterials

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The department offers graduate programs leading to both the Master of Science and Doctor of Philosophy degrees. Exciting opportunities exist for interdisciplinary research. Faculty conduct research in a number of areas including:

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- Hazardous waste treatment
- Particle technology
- Pharmaceutical engineering
- Nanotechnology

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P. Armenante; University of Virginia
B. Baltzis; University of Minnesota
R. Barat; Massachusetts Institute of Technology
C. Gogos; Princeton University
T. Greenstein; New York University
D. Hahn; Agri. Univ. of Wageningen (Netherlands)
D. Hanesian; Cornell University
M. Howley; Rutgers University
M. Huang; University of Massachusetts
K. Hyun; University of Missouri-Columbia
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N. Loney; New Jersey Institute of Technology
A. Perna; University of Connecticut
R. Pfeffer; New York University
L. Simon; Colorado State University
K. Sirkar; University of Illinois-Urbana
R. Tomkins; University of London (UK)
J. Wu; University of Delaware
M. Xanthos; University of Toronto (Canada)

For further information contact:

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  - Transport Phenomena, Electrochemistry, Environmental Engineering
- **Ron K. Bhada**, Professor Emeritus, *University of Michigan*
- **Joe L. Creed**, Assistant Dean, *New Mexico State University*
  - Engineering Design
- **Francisco R. Del Valle**, College Professor, *Massachusetts Institute of Technology*
  - Food Engineering
- **Shuguang Deng**, Assistant Professor, *University of Cincinnati*
  - Separations, Purification, and Fuel Cell Technology
- **Charles L. Johnson**, Professor and Head, *Washington University-St. Louis*
- **Richard L. Long**, Professor and Associate Head *Rice University*
  - Transport Phenomena, Biomedical Engineering, Separations
- **Martha C. Mitchell**, Associate Professor, *University of Minnesota*
  - Advanced Materials, Statistical Mechanics, Molecular Modeling
- **Stuart H. Munson-McGee**, Professor, *University of Delaware*
  - Advanced Materials, Separations
- **John T. Patton**, Professor Emeritus, *Oklahoma State University*
- **David A. Rockstraw**, Associate Professor, *University of Oklahoma*
  - Separations, Environmental Engineering, Kinetics
- **Rudi V. Roubicek**, Professor Emeritus, *Technical University of Prague*
- **Edward F. Thode**, Professor Emeritus, *Massachusetts Institute of Technology*
- **D. Bruce Wilson**, Professor Emeritus, *Princeton University*

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Areas of Research
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- Biochemical Engineering
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- Electronic Materials
- Kinetics & Reaction Engineering
- Interfacial Science
- Polymer Science
- Nanotechnology
- Enzymology
- Supercritical Fluids
- Catalysis

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- Catalysis
- Microgravity - Advanced materials
- Nanocomposite Membranes
- Semiconductor Materials

Selected Research Topics
- Pharmaceutical compounds from plant cell cultures
- Carbon Nanotubes
- Mixed-Matrix Membrane Separation
- Sickle Cell Adhesion
- Surface Acidity of Ti-silicas
- Tissue Engineering
- Thin Film Heterostructures
- Biosensors

For more information write
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Boston, MA 02115

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Chemical Engineering at Northwestern University

Luis A.N. Amaral, Ph.D., Boston University, 1996
  Complex systems, computational physics, biological networks

Annelise E. Barron, Ph.D., Berkeley, 1995
  Bioseparations, biopolymer engineering

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

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

Buckley Crist, Jr., Ph.D., Duke, 1966
  Polymer science, thermodynamics, mechanics

Joshua S. Dranoff, Ph.D., Princeton, 1960
  Chemical reaction engineering, chromatographic separations

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

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

Vassily Hatzimanikatis, Ph.D., Caltech, 1996
  Computational biotechnology, functional genomics, bioinformatics

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

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

Lyle F. Mockros, Ph.D., Berkeley, 1962
  Biomedical engineering, fluid mechanics in biological systems

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

E. Terry Papoutsakis, Ph.D., Purdue, 1980
  Biotechnology of animal and microbial cells, metabolic engineering, genomics

Bruce E. Rittmann, Ph.D., Stanford, 1979
  In situ bioremediation, biofilms

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

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

Randall Q. Snurr, Ph.D., Berkeley, 1994
  Adsorption and diffusion in porous media, molecular modeling

Melody A. Swartz, Ph.D., M.I.T., 1998
  Biomedical transport phenomena

John M. Torkelson, Ph.D., Minnesota, 1983
  Polymer science, membranes

For information and application to the graduate program, write

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William C. Strieder
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Fax: 1-574-631-8366

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Biological Photonic Devices
Blood Rheology
Catalysis and Reaction Engineering
Combinatorial Materials Synthesis
Combustion Synthesis
Drug Delivery
Electrochemical Processes
Environmentally Conscious Design
Enzyme Encapsulation
Inorganic Membranes
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**Faculty Members**
- M.J. Bagajewicz (Ph.D. California Institute of Technology, 1987)
- B.P. Grady (Ph.D. University of Wisconsin-Madison, 1994)
- R.G. Harrison, Jr. (Ph.D. University of Wisconsin-Madison, 1975)
- J.H. Harwell (Ph.D. University of Texas at Austin, 1983)
- L.L. Lee (Ph.D. Northwestern University, 1971)
- L.L. Lobban (Ph.D. University of Houston, 1987)
- R.G. Mallinson (Ph.D. Purdue University, 1983)
- P.S. McFetridge (Ph.D. University of Bath, UK, 2002)
- M.U. Nollert (Ph.D. Cornell University, 1987)
- E.A. O'Rear, Ill (Ph.D. Rice University, 1981)
- D. Papavassiliou (Ph.D. University of Illinois at Urbana-Champaign, 1996)
- D.E. Resasco (Ph.D. Yale University, 1983)
- J.F. Scamehorn (Ph.D. University of Texas, Austin, 1980)
- D.W. Schmidtke (Ph.D. University of Texas, Austin, 1997)
- R.L. Shambaugh (Ph.D. Case Western Reserve University, 1976)
- V.I. Sikavitsas (Ph.D. University at Buffalo, 2000)

**Research Areas**
- **Bioengineering**
  Genetic engineering, protein production, bioseparations, vascular tissue engineering, cell adhesion, biosensors, orthopaedic tissue engineering
- **Energy & Chemicals**
  Catalytic hydrocarbon processing, natural gas conversion, novel fuel cell components, data reconciliation, hydrogen production, process design retrofit and optimization, molecular thermodynamics, computational modeling of turbulent transport and reactive flows, detergency, applied surfactant technologies
- **Materials Science & Engineering**
  Catalytic SWNT production and functionalization, polymer melt blowing, polymer characterization and structure-property relationships, polymer nanolayer formation and use
- **Environmental Processes**
  Photocatalytic oxidation, catalytic NOx reduction, zero-discharge process engineering, soil and aquifer remediation, surfactant-based water decontamination

For more information, call, fax, write, or e-mail:

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K.A.M. Gasem (Ph.D., Oklahoma State University)
Karen A. High (Ph.D., Pennsylvania State University)
Martin S. High (Ph.D., Pennsylvania State University)
A.J. Johannes (Ph.D., University of Kentucky)
Randy Lewis (Ph.D., Massachusetts Institute of Technology)
Sundarajan V. Madihally (Ph.D., Wayne State University)
R. Russell Rhinehart (Ph.D., North Carolina State University)
James E. Smay (Ph.D., University of Illinois)
D. Alan Tree (Ph.D., University of Illinois)
Jan Wagner (Ph.D., University of Kansas)
James R. Whiteley (Ph.D., Ohio State University)

Research Areas
- Adsorption
- Artificial Intelligence
- Biochemical Processes
- Biomaterials
- Colloids/Ceramics
- Environmental Engineering
- Fluid Flow/CFD
- Gas Processing
- Hazardous Wastes
- Ion Exchange
- Molecular Design
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- Phase Equilibria
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- Solid Freeform Fabrication
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Aziz Ben-Jebria (Univ. of Paris)—Respiratory Fluid Flow and Uptake, Inhalation Toxicology
Ali Borhan (Stanford)—Fluid Dynamics, Transport Phenomena
Wayne R. Curtis (Purdue)—Plant Biotechnology
Ronald P. Danner (Lehigh)—Polymers, Phase Equilibria, Diffusion
J. Larry Duda (Delaware)—Polymers, Diffusion Thermodynamics, Tribology, Fluid Mechanics, Rheology
Kristen Fichthorn (Michigan)—Statistical Mechanics, Fluid-Solid Interfaces, Molecular Simulation
Henry C. Foley (Penn State)—Nanoporous Materials, Heterogeneous Catalysis, Adsorption and Permeation
Jong-in Hahn (University of Chicago)—Nano-Biotechnology
Seong Han Kim (Northwestern)—Nano-Tribology and Nano-Materials
Costas D. Maranas (Princeton)—Computational Chemistry, Bioinformatics, Supply Chain Optimization
Janna Maranas (Princeton)—Molecular Simulation, Polymers, Thermodynamics, Network Glasses
Themis Matsoukas (Michigan)—Aerosol Processes, Colloidal Particles, Ceramic Powders
R. Nagarajan (SUNY at Buffalo)—Colloid and Polymer Science
Joseph M. Perez (Penn State)—Tribology, Lubrication
Michael Pishko (Texas)—Bio-materials, Bio-sensing, and Tissue Engineering
James S. Ultman (Delaware)—Physiological Transport Processes, Respiratory Mass Transfer
M. Albert Vannice (Stanford)—Heterogeneous Catalysis
Darrell Velegol (Carnegie Mellon)—Colloidal and Nanoparticle Systems, Bacterial Adhesion
James S. Vrentas (Delaware)—Transport Phenomena, Applied Mathematics, Diffusion in Polymers, Rheology
Andrew Zydney (Massachusetts Institute of Technology)—Biomedical Engineering, Bioseparations, and Membrane Processes

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- Chemical Promotion
- Novel Materials
- Organometallic Chemistry

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- Bioremediation
- Clean Fuels From Coal
- Contaminated Soil Cleanup
- Stack Gas Cleanup

Materials Engineering
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- Polymer/Composite Modeling
- Polymer Processing

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- Molecular Modeling
- Polymer-Fluid Interactions
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B. Garetz
Interactions of lasers with molecules, polarization effects

C. Georgakis
Modeling and control of chemical processes, systems engineering

M. Green
Chirality of macromolecules, liquid crystals

R. Gross
Biosynthesis, biocatalysis and biotechnology

K. Levon
Conductive polymers, biosensors

J. Mijovic
Relaxation dynamics in polymers and biological systems

J. Pinto
Design, scheduling and optimization of chemical processes

L. Stiel
Thermodynamics and transport properties of fluids

I. Teraoka
Separation of polymers, confined systems

A. Ulman
Surface science and engineering, nanotechnology

E. Wolf
Electron tunneling phenomena, nanoscale materials, superconductivity

E. Ziegler
Air pollution control engineering

J. Zlatanova
Chromatin structure and dynamics

W. Zurawsky
Plasma polymerization, polymer thin films
Princeton University

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

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Jay B. Benziger
Jeffrey D. Carbeck
Pablo G. Debenedetti (Chair)
Christodoulos A. Floudas
Yannis G. Kevrekidis
Morton D. Kostin
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http://engineering.purdue.edu/ChE

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The Chemical 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.E. 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.eng.rpi.edu/dept/chem-eng/

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Troy, NY 12180-3590
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http://www.rpi.edu/dept/grad-services/

Faculty and Research Interests

Michael M. Abbott, abbotm2@rpi.edu, Prof. Emeritus
Thermodynamics; equations of state; phase equilibria

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

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

B. Wayne Bequette, bequeb@rpi.edu
Acting Department Chair
Process modeling, control, design, and optimization

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

Timothy S. Cale, calet@rpi.edu
Semiconductor materials processing; transport and reaction analyses

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

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

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

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

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Microelectronics; reverse osmosis; crystal growth; ceramic composites

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Polymers; biosurfaces; biomaterials; nanomaterials

Sanat K. Kumar, kumar@rpi.edu
Polymer nanostructures, nanocomposites, dynamics of glasses and gels, thermodynamics of complex fluids

Howard Littman, littmh@rpi.edu, Professor Emeritus
Fluid/particle systems; fluidization, spouting, pneumatic transport

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

E. Bruce Nauman, nauman@rpi.edu
Polymer blends; nonlinear diffusion; devolatilization; polymer structure and properties; plastics recycling

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

Hendrick C. Van Ness, vanneh@rpi.edu
Institute Professor Emeritus

Peter C. Wayner, Jr., wayner@rpi.edu
Heat transfer; interfacial phenomena; porous materials
Rice University

Chemical Engineering at Rice University

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- Constantine D. Armeniades (Case Western Reserve, 1969)
- Walter G. Chapman (Cornell, 1988)
- Sam H. Davis, Jr.† (MIT, 1957)
- J. David Hellums† (Michigan, 1961)
- Joe W. Hightower† (Johns Hopkins, 1963)
- George J. Hirasaki (Rice, 1967)
- Riki Kobayashi† (Michigan, 1951)
- Paul E. Laibinis (Harvard University, 1991)
- Nikolaos V. Mantzaris (Minnesota, 2000)
- Clarence A. Miller (Minnesota, 1966)
- Matteo Pasquali (Minnesota, 2000)
- Michael S. Wong (MIT, 2000)
- Kyriacos Zygourakis (Minnesota, 1981)

Joint with Bioengineering

- Lary V. McIntire (Princeton, 1970)
- Antonios G. Mikos (Purdue, 1988)
- Ka-Yiu San (Caltech, 1984)
- Jennifer L. West (Texas, 1996)

† Emeritus Faculty

THE UNIVERSITY

- Rice is a leading research university—small, private, and highly selective—distinguished by a collaborative, highly interdisciplinary culture
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FACULTY RESEARCH AREAS

- Biochemical Engineering
- Biomedical Engineering
- Complex Fluids
- Computational Engineering
- Control and Optimization
- Environmental Remediation
- Equilibrium Thermodynamic Properties
- Fluid Mechanics
- Interfacial Phenomena
- Kinetics and Catalysis
- Nanotechnology
- NMR Properties of Fluids
- Petroleum Engineering
- Polymer Science
- Reaction Engineering
- Rheology
- Statistical Mechanics
- Tissue Engineering
- Transport Phenomena

For more information and graduate program applications, write to:

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Chemical Engineering Department, MS-362
Rice University
P.O., Box 1892
Houston, TX 77251-1892
http://www.rice.edu/ceng

Or visit our website at:
Department of Chemical Engineering

University of Rochester

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S. H. CHEN, Ph.D. 1981, Minnesota
  Polymer Science and Engineering • Organic Materials for Optics and Photonics • Molecular Dynamics Simulation

E. H. CHIMOWITZ, Ph.D. 1982, Connecticut
  Critical Phenomena • Statistical Mechanics of Fluids • Computer-Aided Design

D. R. HARDING, Ph.D. 1986, Cambridge (England)
  Chemical Vapor Deposition • Mechanical and Transport Properties • Advanced Aerospace Materials

S. D. JACOBS, Ph.D. 1975, Rochester
  Optics, Photonics, and Optoelectronics • Magnetorheology • Optics Manufacturing

J. JORNE, Ph.D. 1972, California (Berkeley)
  Electrochemical Engineering • Microelectronics Processing • Theoretical Biology

L. J. ROTHBERG, Ph.D. 1984, Harvard
  Organic Materials and Device Sciences • Light-Emitting Diodes • Thin Film Transistors

Y. SHAPIR, Ph.D. 1981, Tel Aviv (Israel)
  Critical Phenomena • Transport in Disordered Media • Scaling Behavior of Growing Surfaces

S. V. SOTIRCHOS, Ph.D. 1982, Houston
  Reaction Engineering • Transport and Reaction in Porous Media • Processing of Ceramic Materials and Composites

J. H. D. WU, Ph.D. 1987, M.I.T.
  Biochemical Engineering • Fermentation • Biocatalysis • Bone Marrow Tissue Engineering • Genetic and Protein Engineering

H. YANG, Ph.D. 1998, Toronto
  Nanstructured Materials • Magnetic Nanoparticles • Mesoporous Solids • Micro- and Nanofabrication • Materials and Structures for Photonics and Biophotonics

M. YATES, Ph.D. 1999, Texas (Austin)
  Colloids and Interfaces • Materials Synthesis in Microemulsions • Nanoparticle/Polymer Composites • Supercritical Fluids • Microencapsulation

For further information and application, write

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  e-mail: gradadm@che.rochester.edu
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Located in southern New Jersey, the nearby orchards and farms are a daily reminder that this is the Garden State. Cultural and recreational opportunities are plentiful in the area. Philadelphia and the scenic Jersey Shore are only a short drive away, and major metropolitan areas are within easy reach.

Faculty
C. Stewart Slater, Chair • Rutgers University
Kevin Dahm • Massachusetts Institute of Technology
Stephanie Farrell • New Jersey Institute of Technology
Zenaida Gephardt • University of Delaware
Robert P. Hesketh • University of Delaware
Kathryn Hollar • Cornell University
James Newell • Clemson University
Mariano J. Savelski • University of Oklahoma

Research Areas
Membrane Separations • Reaction Engineering • Mammalian & Insect Cell Culture • Pharmaceutical and Food Processing Technology • Biochemical Engineering • Green Engineering • Controlled Release • Novel Separation Processes • High-Performance Polymer Processing • Process Design and Optimization • Particle Technology • Supercritical Fluids • Environmental Engineering

For Additional information
Dr. Mariano J. Savelski . Graduate Student Advisor . Department of Chemical Engineering Rowan University . 201 Mullica Hill Road . Glassboro, NJ 08028
Phone: (856) 256-5310 * Fax: (856) 256-5242 * E-mail: savelski@rowan.edu * Web: http://engineering.eng.rowan.edu

Fall 2003
Graduate Program in Chemical & Biochemical Engineering

Research Areas

Biotechnology • Reaction Engineering • Process Systems Engineering • Pharmaceutical Engineering • Polymers

Faculty

Helen M. Buettner, Associate Professor, Ph.D., University of Pennsylvania, 1987 • Applied neurobiology, cell motility, cell-substrate interactions, crystallization of pharmaceuticals

Yee C. Chiew, Professor, Ph.D., University of Pennsylvania, 1984 • Statistical thermodynamics, microscopic structures of fluids and particle systems, interfacial phenomena

Alkis Constantinides, Professor, D.E.Sc., Columbia University, 1970 • Biochemical engineering, optimization and control of fermentation processes, applied numerical analysis, artificial intelligence

Peter Couchman, Professor, Ph.D., University of Virginia, 1976 • Thermodynamics, transition, and equation of state behavior of single and multicomponent systems, particularly polymers; surface phenomena

Burton Z. Davidson, Professor, Ph.D., P.E., Northwestern University, 1965 • System simulation and optimization, environmental engineering, health and safety engineering management

Panos G. Georgopoulos, Associate Professor, Ph.D., California Institute of Technology, 1986 • Atmospheric/environmental chemical engineering, turbulent transport, biochemical modeling

Benjamin J. Glasser, Assistant Professor, Ph.D., Princeton, 1995 • Multiphase flows and reactors; granular materials and particulate suspensions; nonlinear dynamics of transport processes

Masanori Hara, Professor, Ph.D., Kyoto University, 1981 • Polymer physics; polymer chemistry; polymer blends and composites; ionic polymers

Marianthi G. Ierapetritou, Assistant Professor, Ph.D., Imperial College, 1995 • Process systems engineering; process design, planning, and scheduling; uncertainty and environmental considerations; nonlinear and mixed integer optimization

Johannes G. Khinast, Assistant Professor, Ph.D., Graz, 1995 • Reaction and environmental engineering; reactive flows, numerical analysis of large dynamical systems

Michael T. Klein, Dean and Board of Governors Professor of Engineering, Sc.D., MIT, 1981 • Kinetics, catalysis and reaction engineering; automated kinetic modeling; hydrocarbon conversion; reactions in supercritical fluids

Prabhjot V. Moghe, Associate Professor, Ph.D., University of Minnesota, 1993 • Cell and tissue engineering; cell-biomaterial interactions; biomimetic materials

Fernando Muzzio, Professor, Ph.D., University of Massachusetts, 1991 • Transport phenomena; mixing, chaotic flows; powder technology

Henrik Pedersen, Professor, Ph.D., Yale University, 1978 • Biochemical engineering; immobilized enzymes; plant cell biotechnology; fiber-optic sensors

Charles M. Roth, Assistant Professor, Ph.D., University of Delaware, 1994 • Nucleic acid biotechnology; molecular biophysics and bioengineering; bioseparations

Jerry L. Schelbein, Professor, Ph.D., University of Pittsburgh, 1975 • Polymer electrophoresis; structure-selective properties relationships in polymeric materials, ferroelectric, piezoelectric, pyroelectric, dielectric and electrostrictive properties of polymers

M. Silvina Tomassone, Assistant Professor, Ph.D., Northeastern University, 1998 • Molecular dynamics, interfacial analysis, phase transitions

Shaw S. Wang, Professor, Ph.D., Rutgers University, 1970 • Kinetics and thermodynamics of food process engineering, and studies of biochemical and biological processes.

Martin L. Yarmush, Professor, Ph.D., Rockefeller University, 1979 M.D., Yale University, 1984 • Applied immunology, artificial organs, bioseparations, protein engineering, biotechnology

FELLOWSHIPS, TRAINEESHIPS, AND ASSISTANTSHIPS AVAILABLE

For further information contact:
Graduate Program in Chemical and Biochemical Engineering • Rutgers, The State University of New Jersey
School of Engineering • 98 Brett Road • Piscataway, NJ 08854-8058 • Phone (732) 445-4950 • Fax (732) 445-2421
Email: cbemail@sol.rutgers.edu • http://sol.rutgers.edu
National University of Singapore is internationally acknowledged as one of the best universities in the Asia Pacific region, with a global outlook and focus on quality teaching, research and entrepreneurship. With more than 45 faculty members from diverse ethnic backgrounds and with excellent academic credentials from leading institutions around the world, the Department of Chemical and Environmental Engineering offers graduate programs that provide a stimulating and challenging learning experience. The Department has comprehensive top-notch research facilities for carrying out cutting edge research. Close ties with the industry and overseas institutions provide infusion of new ideas and maintain a creative and dynamic atmosphere in the Department.

GRADUATE PROGRAMS

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• Master of Science (Chemical Engineering)
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• Master of Science (Environmental Engineering)
• Master of Science (Safety, Health & Environmental Technology)
• NUS-UIUC Joint Master of Science (Chemical Engineering)

Research-based
• Master of Engineering
• Doctor of Philosophy
• NUS-UIUC Joint PhD Program

Financial assistance is available for qualified applicants in the form of research scholarships.
The Department of Chemical Engineering at USC is booming! Research funding is at an all-time high—exceeding $4 million per year. This progressive department, with its dynamic young faculty, is already recognized as one of the top teaching and research programs in the Southeast. Chemical Engineering offers MS, ME, and PhD degrees, and PhD candidates are offered tuition reduction and highly competitive, twelve-month stipends, ranging from $20,100 to $22,500 per year.

For further information:
The Graduate Director, Department of Chemical Engineering, Swearingen Engineering Center, University of South Carolina, Columbia, SC 29208
Phone: 1-800-763-0527 • Fax: 1-803-777-8265
Web page: www.che.sc.edu

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

Faculty
M.D. Amiridis, Wisconsin
J.W. Bender, Delaware
P.B. Balbuena, Texas
F.A. Gadala-Maria, Stanford
E.P. Gatzke, Delaware
J.H. Gibbons, Pittsburgh
M.A. Matthews, Texas A&M
T. Papathanasiou, McGill
H.J. Ploehn, Princeton
B.N. Popov, Illinois
J.A. Ritter, SUNY Buffalo
T.G. Stanford, Michigan
V. Van Brunt, Tennessee
J.W. Van Zee, Texas A&M
J.W. Weidner, NC State
R.E. White, Cal-Berkeley
C.T. Williams, Purdue

Research Programs
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Colloids and Interfaces Rheology
Composite Materials Separations
Corrosion Engineering Sol-Gel Processing
Crossflow Filtration Solvent Extraction
Electrochemistry Surface Science
Heterogeneous Catalysis Supercritical Fluids
Molecular Simulations Thermodynamics
Nanotechnology Waste Management
Numerical Methods Waste Processing

Chemical Engineering Education
Faculty
Paschalis Alexandridis (MIT) • amphiphilic polymers, self-assembly, complex fluids, nanomaterials, interfacial phenomena
Stelios T. Andreadis (Michigan) • bioengineering, gene therapy, tissue engineering of genetically modified skin
Jeffrey R. Errington (Cornell) • molecular simulation, statistical thermodynamics, biopreservation
Vladimir Hlavacek (ICT -Prague) • reaction engineering, nanopowders, explosives and detonations, analysis of chemical plants
Mattheos Koffas (MIT) • metabolic engineering, bioinformatics
David A. Kofke (Pennsylvania) • molecular modeling and simulation, solid phase equilibria
Carl R. F. Lund (Wisconsin) • heterogeneous catalysis, chemical kinetics, reaction engineering
T. J. (Lakis) Mountziaris (Princeton) • electronic and photonic materials, nanoparticles, biosensors, multiphase flows
Sriram Neelamegham (Rice) • biomedical engineering, cell biomechanics, vascular engineering
Johannes M. Nitsche (MIT) • fluid mechanics, transport phenomena, bioactive surfaces, biological pores, transdermal transport
Eli Ruckenstein (Bucharest) • catalysis, surface phenomena, colloids and emulsions, biocompatible surfaces and materials
Michael E. Ryan (McGill) • polymer and ceramics processing, rheology, non-Newtonian fluid mechanics
Mark T. Swihart (Minnesota) • chemical kinetics, modeling of reactive flows, computational chemistry, nanoparticle formation
E. (Manolis) S. Tzanakakis (Minnesota) • cell and tissue engineering, biochemical engineering

Adjunct Faculty
V. James Hernandez (Microbiology) • regulation of cellular responses
William M. Mihalko (School of Medicine) • orthopaedics
Bruce Nicholson (Biological Sciences) • gap junctions and connexins
Athos Petrou (Physics) • spectroscopy, semiconductor nanostructures
Carol Jan van Oss (Microbiology) • colloid and interface science
Yaoqi Zhou (Biophysics) • protein folding, simulation of biomolecules

Emeritus Faculty in Residence
Robert J. Good (Michigan) • adhesion and interface science, philosophy of science
Thomas W. Weber (Cornell) • process control
Sol W. Weller (Chicago) • catalysis, coal liquefaction, history of chemical engineering

Chemical engineering faculty participate in many interdisciplinary centers and initiatives, including The Center for Advanced Molecular Biology and Immunology, The Center for Computational Research, The Center for Advanced Photonic and Electronic Materials, The Institute for Lasers, Photonics, and Biophotonics, The Institute for Bioinformatics, and The Center for Advanced Technology for Biomedical Devices

For more information and an application, write to: Director of Graduate Studies, Department of Chemical Engineering, University at Buffalo (SUNY), Buffalo, New York, 14260-4200, or go to http://www.cheme.buffalo.edu

All Ph.D. students are supported as research or teaching assistants. Additional fellowships sponsored by Praxair, Inc., The National Science Foundation IGERT program, and the State University of New York are available to exceptionally well-qualified applicants.
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**Faculty**

R. Besser (PhD, Stanford University)
R. Blanks (PhD, University of California at Berkeley)
G.B. DeLancey (PhD, University of Pittsburgh)
H. Du (PhD, Penn State University)
T.E. Fischer (ScD, Federal Inst. of Technology, Zurich)
B. Gallois (PhD, Carnegie-Mellon University)
D.M. Kalyon (PhD, McGill University)
S. Kovenkiloglu (PhD, Stevens Institute of Technology)
A. Lawal (PhD, McGill University)
W.Y. Lee (PhD, Georgia Institute of Technology)
M. Libera (ScD, Massachusetts Inst. of Technology)
A. Ritter (Ph.D., University of Rochester)
G. Rothberg (PhD, Columbia University)
K. Sheppard (PhD, University of Birmingham)

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Graduate students and faculty working together to reach common goals—that partnership is at the heart of The University of Tennessee-Knoxville’s Department of Chemical Engineering. It’s a partnership that works, creating exciting and productive research in five major areas: (1) biochemical and environmental engineering, (2) molecular modeling and thermodynamics, (3) reaction and separation processes, (4) rheology and polymer processing, and (5) process control. These research programs reach out to other engineering and science departments, to the nearby Oak Ridge National Laboratory, and to industry, forming larger partnerships and creating an unsurpassed research environment.

The University

Founded in 1794 as Blount College, the first non-sectarian college west of the Appalachians, The University of Tennessee today is the state’s largest university and Land-Grant institution with about 20,000 undergraduates, 5,700 graduate and professional students, and a faculty of 1,200. The University of Tennessee is located in Knoxville near the headwaters of the Tennessee River. Within an hour’s drive are six Tennessee Valley Authority lakes and the Great Smoky Mountains National Park. The Knoxville metropolitan area has a population of 600,000 but enjoys a pleasant, generally uncrowded atmosphere and consistently ranks among the nation’s top ten metropolitan areas in surveys on quality of life. East Tennessee has a four-season climate, ranging from warm summer temperatures to winter temperatures cold enough for snow skiing in nearby mountain resorts.

For additional information contact:
Department of Chemical Engineering
University of Tennessee-Knoxville
419 Dougherty Hall
Knoxville, TN 37996-2200
Phone: (865) 974-2421
Email: cheinfo@utk.edu
http://www.che.utk.edu

The Faculty

Paul R. Bienkowski (Ph.D., Purdue, 1975)  
Bioprocessing, Thermodynamics

Duane D. Bruns (Ph.D., Houston, 1974)  
Process Control, Modeling

John R. Collier (Ph.D., Case Institute, 1966)  
Polymer Processing and Properties

Robert M. Counce (Ph.D., Tennessee, 1980)  
Green Engineering, Design, Separations

Brian J. Edwards (Ph.D., Delaware, 1991)  
Non-Newtonian Fluid Dynamics

Paul D. Frymier (Ph.D., Virginia, 1995)  
Biochemical Engineering, Biosensors

David J. Keffer (Ph.D., Minnesota, 1996)  
Molecular Modeling of Adsorption, Diffusion and Reaction in Zeolites

Charles F. Moore (Ph.D., Louisiana State, 1969)  
Process Control

Tsewei Wang (Ph.D., M.I.T., 1977)  
Process Control, Bioprocessing

Frederick E. Weber (Ph.D., Minnesota, 1982)  
Radiation Chemistry, Engineering Pedagogy

Adjunct and Part-Time Faculty from Oak Ridge National Laboratory

Hank D. Cochran (Ph.D., M.I.T.)  Thermodynamics, Statistical Mechanics

Brian H. Davison (Ph.D., Caltech)  Biochemical Engineering
Research areas

Electrical Field-Based Processes and Systems
Micro-devices for free flow fractionation and micro-electrophoresis • electrokinetics soil remediation • electroosmotic flow of particles in processing fluids • electrical-based corona high oxidation processes • modeling, multi-scale simulation and analysis of batteries and fuel cells and other electrochemical systems for hybrid vehicle applications • estimation of transport and kinetic parameters of batteries using AC impedance spectroscopy

Biological Engineering Processes and Systems
Metabolic pathways, enzyme catalyzed reactions and kinetics • alcohol metabolism • pharmacokinetics and drug delivery • bioinformatics • biological microflows in the human body • separation of bio-macromolecules, biosensors • design and characterization of artificial environments for bio-growth • thermodynamic and transport properties

Molecularly-based Engineered Materials and Interfacial Systems
Multi-scale approach to material design, synthesis, and characterization • micro- and nanoscale engineering of soft (gels) and advanced cement-based materials • micro-rheology of macromolecules in reduced environments • single-molecule fluorescence microscopy spectroscopy • transport properties in porous structure systems • design and characterization of foam blowing agents

Computational Mathematics
Method of lines • computational design of complex fluid mixtures • MC and molecular dynamics simulations • modeling of multiphase and reacting systems • novel methods for phase equilibria calculations

Engineering Education
Systems-based learning environments • high performance learning environments • problem-based learning • social learning theory applications • cognitive apprenticeship and writing • ABET-based models of assessment

Tennessee Tech University

With new leadership and an energetic faculty, Tennessee Tech's Chemical Engineering Department blends scholarship and research with advanced studies, offering excellent opportunities to graduate students. The dynamic and flexible graduate program offers an M.S. in Chemical Engineering and a Ph.D. in Engineering with a concentration in Chemical Engineering. The program's interdisciplinary nature lends itself to relevant projects in current areas of research. Within this framework, the core faculty enhances student opportunities by working closely with faculty in Environmental and Civil Engineering, Mechanical Engineering, Chemistry, Biology, and Manufacturing and Industrial Technology to build a unique and effective environment for graduate research and learning.

Currently, the program supports three major areas of research: Electrical Field-based Systems and Processes, Biological Systems and Processes, and Molecularly-based Engineering Materials and Interfacial Systems. Two "envelope areas" are also active: Computational Mathematics and Engineering Education. The relatively small size of the program and friendly atmosphere of the university promote close interaction among students and faculty. Opportunities to mentor undergraduate students in research and in the use of instruments such as NMR, electron microscopy, x-ray diffraction and microflow visualization lead to well-rounded training as does the department's partnership with faculty and staff from TTU's Centers of Excellence in Manufacturing Research, Water Resources, and Electric Power, as well as researchers from Oak Ridge and Sandia national laboratories. Graduate students are continually exposed to a vibrant and dynamic program in our department.

Core Faculty in Chemical Engineering
Pedro E. Arce, Ph.D., Purdue
Joseph B. Biernacki, Sci. Degree, Cleveland State
Richard Booth, Ph.D., Clemson
Patricia Dycus, Ph.D., In. Tech
Vankat R. Subramanian, Ph.D., University of South Carolina
Donald P. Visco, Jr., Ph.D., SUNY-Buffalo
David Whitmire, Ph.D., Auburn

Collaborating Faculty
Jeffrey O. Boles, Chemistry, Ph.D., South Carolina
Glenn Cunningham, Mechanical, Ph.D., Tennessee Tech
Ahmed ElSawy, Industrial and Manufacturing, Ph.D., Cairo Univ.
Dennis George, Environmental Systems, Ph.D., Clemson
Martha J.M. Wells, Chemistry, Ph.D., Auburn

Emeritus
Clayton P. Kerr, Ph.D., Louisiana State
William D. Holland, Ph.D., Georgia Tech
John C. McGee, Ph.D., North Carolina State
David W. Yarbrough, Ph.D., Georgia Tech

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For more information, please contact
Dr. Joseph J. Biernacki, Graduate Program Coordinator
E-mail: jbiernacki@tntech.edu
Phone (931) 372-3567 • Fax (931) 372-6352
Write to TTU Chemical Engineering Department, Box 5013, Cookeville, TN 38505-0001
Visit www.tntech.edu/che

Tennessee Tech University is a constituent university of the Tennessee Board of Regents/An EEO/AA/Title IX/Section 504/ADA University
Chemical Engineering at the University of Texas at Austin is an exciting, broad-based and interdisciplinary program, with faculty of diverse research interests. We are one of the leading programs in chemical engineering excelling in all aspects of scholarship, research and education. Both M.S. ChE and Ph.D. ChE degrees are offered. Fellowships and research assistantships are provided, including tuition and fees.

Faculty and their research

David T. Allen, Ph.D., Caltech, 1983 • environmental modeling, reaction engineering
Roger T. Bonnecaze, Ph.D., Caltech, 1991 • suspension rheology, transport phenomena, electrical impedance tomography
Thomas F. Edgar, Ph.D., Princeton U., 1971 • process modeling, control, optimization
John G. Ekerdt, Ph.D., U. of C. Berkeley, 1979 • electronic materials chemistry, surface science
R. Bruce Eldridge, Ph.D., U. of Texas, 1986 • separations research
Benny D. Freeman, Ph.D., U. of C. Berkeley, 1988 • polymer structures, processing and properties
Venkat Ganesan, Ph.D., MIT, 1999 • statistical mechanics, simulations of self-assembly in complex fluids
George Georgiou, Ph.D., Cornell U., 1987 • microbial, protein biotechnology
Peter F. Green, Ph.D., Cornell U., 1985 • materials science, polymer melts
Adam Heller, Ph.D., Hebrew U., 1961 • electrochemical biosensing, environmental photoelectrochemistry
Gyeong S. Hwang, Ph.D., Caltech, 1999 • multiscale modeling & simulation, semiconductors, nanotechnology
Keith P. Johnston, Ph.D., U. of Illinois, 1981 • polymer and surface thermodynamics, supercritical fluids
Miguel José-Yacaman, Ph.D., National University of Mexico, 1973 • materials science, electron microscopy, nanoparticles
Brian A. Korgel, Ph.D., U. of C. Los Angeles, 1997 • complex fluids, nanostructured materials
Douglas R. Lloyd, Ph.D., U. of Waterloo, 1977 • polymeric membrane formation, liquid separations
Yueh-Lin Loo, Ph.D., Princeton U., 2001 • polymer physics & chemistry, micro- & nanostructured materials
C. Buddie Mullins, Ph.D., Caltech, 1990 • surface science, molecular beams, nanostructured film growth
Donald R. Paul, Ph.D., U. of Wisconsin, 1965 • polymer blends, membranes, barrier materials
Nicholas A. Peppas, Sc.D., MIT, 1973 • polymer physics, biomaterials, controlled drug delivery
S. Joseph Qin, Ph.D., U. of Maryland, 1992 • process modeling and control
Gary T. Rochelle, Ph.D., U. of C. Berkeley, 1977 • air pollution control, reactive mass transfer
Peter J. Rossky, Ph.D., Harvard U., 1978 • theoretical chemistry, liquids, condensed phase quantum dynamics
Isaac C. Sanchez, Ph.D., U. of Delaware, 1967 • statistical thermodynamics of polymer liquids and solutions
Christine E. Schmidt, Ph.D., University of Illinois, 1995 • cell and tissue engineering
Mukul M. Sharma, Ph.D., U. of Southern California, 1985 • surface and colloid chemistry
Thomas M. Truskett, Ph.D., Princeton U., 2001 • statistical mechanics, molecular modeling
John M. White, Ph.D., U. of Illinois, 1966 • chemical reactions on surfaces
C. Grant Willson, Ph.D., U. of C. Berkeley, 1973 • polymer synthesis, photochemical processing

Address Inquiries to: Graduate Advisor • Dept. of Chemical Eng. • The University of Texas • 1 University Station Co400 • Austin, TX 78712
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- Computational Chemistry
- Environmental Engineering
- Process Design and Integration
- Biochemical Engineering
- Process Safety
- Thermodynamics
- Advanced Materials
- Catalysis

For More Information
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Texas A&M University • College Station, Texas 77843-3122
Phone (979) 845-3361 • Website http://www.cheweb.tamu.edu

R.G. Anthony • Ph.D., University of Texas, 1966
  C.D. Holland Professor
  Environmental remediation & benign processing, kinetics, catalysis & reaction engineering

A. Akgerman • Ph.D., U. of Virginia, 1971
  Chevron II Professor
  Environmental remediation & benign processing, kinetics, catalysis & reaction engineering

J.T. Baldwin, Ph.D. • Texas A&M University, 1968
  Process, design, integration, and control

M.A. Bevan, Ph.D. • Carnegie Mellon University, 1999
  Colloidal Science

D.B. Bukur • Ph.D., U. of Minnesota, 1974
  Reaction engineering, math methods

J.A. Bullin, Ph.D. • U. of Houston, 1972, Professor Emeritus
  R. Darby, Ph.D. • Rice University, 1972, Professor Emeritus
  Rheology, polymers

R.R. Davison, Ph.D. • Texas A&M U., 1962, Professor Emeritus
  Asphalt characterization

L.D. Durbin, Ph.D. • Rice University, 1961, Professor Emeritus
  M. El-Halwagi, Associate Head, Ph.D. • Univ. of California, 1990
  McFerrin Professor
  Environmental remediation & benign processing, process, design, integration, and control

P.T. Eubank, Ph.D. • Northwestern University, 1961
  Joe M. Nesbitt Professor
  Thermodynamics

D.M. Ford, Ph.D. • University of Pennsylvania, 1996
  Molecular simulation & computational chemistry, thermodynamics, transport and interfacial phenomena

G. Froment, Ph.D. • University of Gent, Belgium, 1957
  Kinetics, catalysis, and reaction engineering

C.J. Glover, Ph.D. • Rice University, 1974
  Materials chemistry, synthesis, and characterization, transport and interfacial phenomena

T. Good, Ph.D. • University of Wisconsin-Madison, 1996
  Biomedical/Biomedical

J. Hahn, Ph.D. • University of Texas, 2002
  Process, design, integration, and control

K.R. Hall, Head, Ph.D. • University of Oklahoma, 1967
  Jack E. and Frances Brown Chair
  Process safety, thermodynamics

D.T. Hanson, Ph.D. • University of Minnesota, 1968
  Biochemical engineering

C.D. Holland, Ph.D. • Texas A&M U., 1953, Professor Emeritus
  Separation processes, distillation, unsteady-state processes

J.C. Holste, Ph.D. • Iowa State University, 1973
  Thermodynamics

M.T. Holtzapple, Ph.D. • University of Pennsylvania, 1981
  Biological/Biochemical

Y. Kuo, Ph.D., Dow Professor • Columbia University, 1979
  Microelectronics

S. Mannan, Ph.D. • University of Oklahoma, 1986
  Director, Mary Kay O'Connor Process Safety Center
  Process safety

E. Sevick-Muraca, Ph.D. • Carnegie Mellon University, 1989
  Biomedical/Biochemical

D.F. Shantz, Ph.D. • University of Delaware, 2000
  Structure-property relationships of porous materials, synthesis of new porous solids

V. Ugaz, Ph.D. • Northwestern University, 1999
  Microfabricated Bioseparation Systems
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.

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Faculty

Martin A. Abraham, Professor
Ph.D., University of Delaware
Green Chemistry and Engineering, Supercritical Fluids

Maria R. Coleman, Associate Professor
Ph.D., University of Texas at Austin
Membrane Separations, Bioseparations

Kenneth J. DeWitt, Distinguished Professor
Ph.D., Northwestern University
Transport Phenomena, Mathematical Modeling & Numerical Methods

John P. Dismukes, Professor
Ph.D., University of Illinois
Materials Processing, Management of Technological Innovation

Isabel C. Escobar, Assistant Professor
Ph.D., University of Central Florida
Membrane Fouling and Membrane Modifications

Saleh Jabarin, Professor
Ph.D., University of Massachusetts
Physical Properties of Polymers, Polymer Orientation & Crystallization

Dong-Shik Kim, Assistant Professor
Ph.D., University of Michigan
Biomaterials, Metabolic Pathway Control

Steven E. LeBlanc, Professor and Chair
Ph.D., University of Michigan
Chemical Process Control, Chemical Engineering Education

G. Glenn Lipscomb, Professor
Ph.D., University of California at Berkeley
Membrane Separations, Bioseparations, Education

Arunan Nadarajah, Professor
Ph.D., University of Florida
Transport in Biological Systems, Nanotechnology

Bruce E. Poling, Professor
Ph.D., University of Illinois
Thermodynamics and Physical Properties

Constance A. Schall, Associate Professor
Ph.D., Rutgers University
Enzyme Kinetics, Crystallization, Paraffin Deposition

Sasidhar Varanasi, Professor
Ph.D., State University of New York at Buffalo
Colloidal & Interfacial Phenomena, Hydrogels
Ranked among the best universities in the country, Tufts is known for technological innovation, cutting-edge research, and dedicated faculty. Chemical and Biological Engineering faculty are actively involved in a wide variety of research projects, including several in the department's Pollution Prevention Laboratory and Bioengineering Center. The department is housed in the Science and Technology Center, a state-of-the-art research and teaching facility, which also houses the cutting-edge interdisciplinary research activities of our Bioengineering Center. Our graduate students develop new technologies and processes at the intersection of chemistry and biology and conduct innovative research that spans the full range of chemical and biological engineering with man-made catalysts to working with enzymes, the catalysts of nature.

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### FACULTY

- **Gregory D. Botsaris**
  - Crystallization, nucleation, applied surface science
- **Maria Flytzani-Stephanopoulos**
  - Environmental catalysis, clean energy, pollution prevention
- **David L. Kaplan**
  - Bioengineered polymers related to self assembly, biomaterials and tissue engineering
- **Kyongbum Lee**
  - Metabolic engineering, biotechnology, bioinformatics
- **Jerry H. Meldon**
  - Membrane science and technology, mass transfer with chemical reaction including mathematical modeling
- **Daniel F. Ryder**
  - Materials science, advanced process control applications
- **Nak-Ho Sung**
  - Polymers and composites, interface science, polymer diffusion, surface modification
- **Kenneth A. VanWormer**
  - Optimization, reaction kinetics, VLSI fabrication

### ADJUNCT AND RESEARCH FACULTY

- **Aurdie Edwards**
  - Biomedical engineering, role of microcirculation in the renal medulla
- **Dale Gyure**
  - Novel therapeutics and nutrition supplements
- **Walter Juda**
  - Membrane processes, electrochemistry, fuel cells
- **Brian Kelley**
  - Novel methods for protein purification, large-scale purifications, high-density bacterial fermentation
- **Ljiljana Kundakovic**
  - Biological reactors
- **Howard Saltsburg**
  - Catalysis, materials science
- **Regina Valluzzi**
  - Molecular biophysics, ordering of highly structured patterned polymers into complex nanostructured materials
- **Vladimir Volloch**
  - Cellular and molecular biology
- **Gordana Vunjak-Novakovic**
  - Biomedical engineering, transport phenomena, tissue engineering, bioreactors
- **Stefan Winkler**
  - Protein assembly
Faculty and Research Areas

Daniel C.R. DeKee • Rheology of Natural and Synthetic Polymers • Constitutive Equations • Transport Phenomena and Applied Mathematics

W T. Godby • Gene Delivery • Cellular Engineering • Molecular Aspects of Nonviral Transfection • Biomaterials

Richard D. Gonzalez • Synthesis and Characterization of Supported Metal Catalysts • Fundamental Studies in Reactor Design • In-situ Spectroscopic Methods • Reactions in Organized Media

Vijay T. John • Biomimetic and Nanostructured Materials • Interfacial Phenomena • Polymer-Ceramic Composites • Surfactant Science

Victor J. Law • Modeling Environmental Systems • Nonlinear Optimization and Regression • Transport Phenomena • Numerical Methods

Yunfeng Lu • Nanostructured and Microelectronic Materials • Sol-Gel Processes and Organic/Inorganic Hybrid Materials • Membrane Separations and Catalysts • Chemical Sensors and Biosensors

Brian S. Mitchell • Fiber Technology • Materials Processing • Composites

Kim C. O'Connor • Animal-Cell Technology • Organ/Tissue Regeneration • Recombinant Protein Expression

Kyriakos D. Papadopoulos • Colloid Stability • Coagulation • Transport of Multiphase Systems Through Porous Media • Colloidal Interactions

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Tulane is located in a quiet, residential area of New Orleans, approximately six miles from the world-famous French Quarter. The chemical engineering department currently enrolls approximately 40 full-time graduate students. Graduate fellowships include a tuition waiver plus stipend.
The University of Tulsa is Oklahoma's oldest and largest independent university. Approximately 4,200 students pursue more than 70 major fields of study and graduate programs in more than 25 disciplines.

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Off-campus activities abound in Tulsa, one of the nation's most livable cities. Our temperate climate, with four distinct seasons, is perfect for year-round outdoor activities. With a metropolitan population of 450,000, the city of Tulsa affords opportunities for students to gain internship and work experience in its dynamic data processing, petroleum, medical, and financial industries. One can also enjoy world-class ballet, symphony and theatre performances, and exhibits in the cultural community. Annual events include Mayfest, Oktoberfest, the Chili Cook-off and Bluegrass Festival, the Tulsa Run, and the Jazz and Blues festivals.

Chemical Engineering at TU

TU enjoys a solid international reputation for expertise in the petroleum industry, and offers environmental and biochemical programs. The department places particular emphasis on experimental research, and is proud of its strong contact with industry.

The department offers a traditional Ph.D. program and three master’s programs:

- Master of Science degree (thesis program)
- Master of Engineering degree (a professional degree that can be completed in 18 months without a thesis)
- Special Master’s degree for nonchemical engineering undergraduates

Financial aid is available, including fellowships and research assistantships.

The Faculty

D.W. Crunkleton • Fuel cells, sensors
L.P. Ford • Kinetics of dry etching of metals, surface science
K.D. Luks • Thermodynamics, phase equilibria
F.S. Manning • Industrial pollution control, surface processing of petroleum
C.L. Patton • Thermodynamics, applied mathematics
G.L. Price • Zeolites, heterogeneous catalysis
K.L. Sublette • Bioremediation, biological waste treatment, ecological risk assessment
K.D. Wisecarver • Multiphase reactors, multiphase flows

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Graduate work in chemical engineering provides an opportunity for study and research at the cutting edge - to contribute to shaping a new model of what chemical engineering is and what chemical engineers do. Formal course work for the Ph.D. essentially doubles the exposure to chemical engineering principles that students receive as undergraduates. Thesis research gives unparalleled experience in problem solving, the key to challenging research assignments in industry and admission to the worldwide community of scholars.

http://www.vuse.vanderbilt.edu/~cheinfo/che.htm

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Giorgio Carta, PhD, University of Delaware
Adsorption, ion exchange, biocatalysis, environmentally benign processing

Robert J. Davis, PhD, Stanford University
Heterogeneous catalysis, characterization of metal clusters, reaction kinetics

Erik J. Fernandez, PhD, University of California, Berkeley
Purification of biological molecules, protein structure, magnetic resonance imaging and spectroscopy

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

John L. Gainer, PhD, University of Delaware
Biochemical engineering, biomedical applications, environmentally benign solvents

John L. Hudson, PhD, Northwestern University
Reaction system dynamics, chaos and pattern formation, electrochemistry

Cato Laurencin, MD, Harvard Medical School
PhD, Massachusetts Institute of Technology
Biomaterials, tissue engineering, nanotechnology

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

James P. Oberhauser, PhD, University of California, Santa Barbara
Polymer solution flow and microstructure

John P. O'Connell, PhD, University of California, Berkeley
Molecular theory and simulation with applications to physical and biological systems
Chemical Engineering at Virginia Tech

Gateways of Opportunity

Research Centers and Focus Areas

- Polymer Materials and Interface Laboratory
- Center for Composite Materials and Structures
- Center for Adhesives and Sealant Science
- Center for Biomedical Engineering
- Center for Self-Assembled Nanostructures and Devices
- Biotechnology and Tissue Engineering
- Surface Chemistry and Catalysis
- Colloid and Surface Science
- Computer-aided Design
- Nanotechnology and Biomedical Devices
- Supercritical Fluids and High Pressure Processing

Faculty...

Donald G. Baird (Wisconsin)
Polymer processing, non-Newtonian fluid mechanics

David F. Cox (Florida)
Catalysis, ultrahigh vacuum surface science

Richey M. Davis (Princeton)
Colloids and polymer chemistry, nanostructured materials

Kimberly E. Forsten-Williams (Illinois)
Computational bioengineering and cell and tissue engineering

Aaron S. Goldstein (Carnegie Mellon)
Tissue engineering, interfacial phenomena in bioengineering

Erdogan Kiran (Department Head) (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

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

Ravi Saraf (Massachusetts)
Nanotechnology and biomedical devices, polymers

Joseph T. Sullivan (Minnesota)
Marketing and chemical distribution

Kevin E. Van Cott (Virginia Tech)
Biotechnology, nanotechnology

William H. Velander (Penn State)
Transgenic livestock bioreactors, biosensors

Garth L. Wilkes (Massachusetts)
Structure-property processing behavior of polymeric materials

Virginia Tech

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———
Chemical Engineering Faculty • Research Areas
———

Materials and Interfacial Phenomena
Stuart Adler, Ph.D., California (Berkeley) • Electrochemical Engineering; Solid-State Electrochemistry
G. Graham Allan (Joint), Ph.D., D.Sc., Glasgow • Fiber and Polymer Science
John C. Berg, Ph.D., California (Berkeley) • Interfacial Phenomena; Surface and Colloid Science
Samson A. Jenekhe, Ph.D., Minnesota • Polymer Science & Engineering; Optoelectronic/Photonic Materials
Shaoyi Jiang, Ph.D., Cornell • Interfacial Phenomena and Nanotechnology
René M. Overney, Ph.D., Basel, Switzerland • Nanoscale Surface Science and Polymer Physics
Daniel T. Schwartz, Ph.D., California (Davis) • Electrochemical Engineering; Electrolytic Thin-Film Science
James C. Seferis, Ph.D., Delaware • Polymeric Composites; Manufacturing and Teaming
Eric M. Stuwe, Ph.D., Stanford • Electrochemical Surface Science; Fuel Cell Electrocatalysis

Biochemical Engineering and Bioengineering
François Baneyx, Ph.D., Texas (Austin) • Biotechnology; Protein Technology; Biochemical Engineering
David G. Castner, Ph.D., California (Berkeley) • Biomaterial and Biomolecule Surface Analysis, Self-Assembled Monolayers
Thomas A. Horbett (Joint), Ph.D., Washington • Biomaterials; Peptide Drug Delivery
Mary E. Lidstrom, Ph.D., Wisconsin • Environmental Biotechnology; Molecular Bioengineering
Buddy D. Ratner (Joint), Ph.D., Brooklyn Polytechnic • Biomaterials; Polymers; Surface Characterization

Information and Process Technology
Bruce A. Finlayson, Ph.D., Minnesota • Mathematical Modeling
Bradley R. Holt, Ph.D., Wisconsin • Process Design and Control
N. Lawrence Ricker, Ph.D., California (Berkeley) • Process Control and Optimization

Environmental Technology
E. James Davis, Ph.D., Washington • Colloid Science; Aerosol Chemistry and Physics; Electrokinetics
Barbara Krieger-Brockett, Ph.D., Wayne State • Reaction Engineering
Graduate Programs in

Chemical Engineering

Master's and doctoral programs in WSU's Department of Chemical Engineering offer you a world-class environment for research and scholarship with a comprehensive graduate curriculum and highest quality faculty members to lead you. The program is closely aligned with industry and government interests that often lead to professional career opportunities.

Our emphases in bioengineering, environmental restoration, and hydrocarbon processing involve you in such projects as biotreatment of hazardous contamination, diagnostic medical devices, and conversion of natural gas to useful products. Our Center for Multiphase Environmental Research provides interdisciplinary opportunities to solve complex environmental problems at the interface of air, water, and earth.

Facilities
Facilities include the Engineering Teaching and Research Laboratory in Pullman, a state-of-the-art building that houses the O.H. Reaugh Advanced Processing Lab. Other venues are the Spokane Intercollegiate Research and Technology Institute and WSU Tri-Cities access to Hanford resources, such as the Environmental Molecular Science Lab and the Hanford Library.

Financial Assistance
All full-time ChemE graduate students at WSU receive financial support to help cover costs of education, living, and insurance.

Student Life
Pullman's residential campus offers single and family housing for graduate students. Families with children have access to highly rated K-12 schools.

Outdoor and recreational activities abound in the nearby mountains, rivers, and forests. Students may belong to the Graduate and Professional Student Association and numerous other student societies.

About WSU
Washington State University is a land-grant research university founded in Pullman in 1890. It enrolls more than 20,000 students at four campuses and numerous Learning Centers throughout the state. As many as 100 advanced degrees are offered from 70 graduate programs within its eight colleges.

Faculty
Cornelius Ivory, Ph.D. Princeton, bioprocessing, separations, modeling
James Lee, Ph.D Kentucky, bioprocessing, mixing
Kristina Liddell, Ph.D. Iowa State, hazardous wastes, materials, electrochemistry, kinetics, chemical equilibria
Reid Miller, Ph.D. University of California–Berkeley, thermodynamics
James Petersen, Ph.D. Iowa State, bioremediation, bioprocessing, subsurface creative flow and transport, optimization
Brent Peyton, Ph.D. Montana State, bio-availability, extremophilic bioprocessing, heavy metal flux in biofilms and porous materials
William Thomson, Ph.D. Idaho, materials, kinetics, catalysis
Bernie Van Wie, Ph.D. Oklahoma, bioprocessing, Biomedical engineering
Richard Zollars, Ph.D. Colorado, colloidal and interfacial phenomena, separations

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Master's and Doctoral Programs

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L. Angenent • Biological Waste Conversion, Bioaerosol Control, Environmental Engineering
P. Biswas • Aerosol Dynamics, Environmental Engineering
M. P. Dudukovic • Multiphase Reaction Engineering, Tracer Methods, Environmental Engineering
J. T. Gleaves • Heterogeneous Catalysis, Surface Science, Microstructured Materials
J. L. Kardos • Composite Materials and Polymer Engineering
B. Khomami • Rheology, Polymer and Composite Materials Processing
P. A. Ramachandran • Chemical Reaction Engineering, Boundary Element Methods
R. Sureshkumar • Complex Fluids Dynamics, Interfacial Nanostructures, Multiscale Modeling and Simulations
J. Turner • Environmental Reaction Engineering, Air Quality Policy and Analysis, Air Pollution Control

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Washington University encourages and gives full consideration to application for admission and financial aid without respect to sex, race, handicap, color, creed or national origin.
Sandro R.P. da Rocha, Ph.D., UT Austin, 2000
Nanostructured materials from self-assembled amphiphiles in conventional and compressible media • Drug delivery and sensing devices • Molecular modeling and computer simulations

Esin Gulari, Ph.D., Caltech, 1973
Thermodynamics and transport properties of polymer solutions and melts • Processing of polymers with supercritical fluids • Light scattering based particle and drop sizing techniques

Yinlun Huang, Ph.D., Kansas State, 1992
Pollution prevention and waste minimization • Process design and synthesis

Rangaramanujam Kannan, Ph.D., Caltech, 1994 — Dynamics of polymeric systems and interfaces • Rheo-optical spectroscopy and scattering techniques

Ralph Kummer, Ph.D., John Hopkins, 1966 — Modeling of combined sewer overflows and sediments • Chemical kinetics • Computer simulation

Joseph F. Louvar, Ph.D., Wayne State, 1983 — Process design and safety • Risk analysis

Charles Manke, Chair, Ph.D., California, Berkeley, 1983 — Polymer processing and rheology • Molecular dynamics and kinetic theory of polymeric liquids

Guang-Zhao Mao, Ph.D., Minnesota, 1994 — Optoelectronic properties of thin films and crystals • Self-assembly of polymers and surfactants • Colloidal stability of waterborne paints • Real time imaging of surface phenomena at the molecular level

Howard Matthew, Ph.D., Wayne State, 1992 — Tissue engineering and biomaterials • Artificial organ substitutes

Simon Ng, Ph.D., Michigan, 1985 — Heterogeneous catalysis • Spectroscopic and thermal analysis of material surfaces

Jeffrey Potoff, Ph.D., Cornell, 1999 — Molecular simulation • Phase behavior • Complex systems

Susil Putatunda, Ph.D., IIT Bombay, 1983 — Effects of microstructure on fatigue • Fracture toughness • Creep in metals and alloys

Erhard Rothe, Ph.D., Michigan, 1959 — Applications of high-powered UV lasers • Machining of electronic chips • Diagnostics of internal combustion

Steven Salley, Ph.D., Detroit, 1976 — Biochemical/medical engineering • Design of artificial organs • Immobilized enzyme reactors

Gina Shreve, Ph.D., Michigan, 1991 — Environmental and biochemical applications • Microbially mediated biotransformations

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

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Biochemical Engineering and Biotechnology
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Multi-Phase Flow • Particle Coating
Polymer Composites • Polymer Rheology
Powder Technology • Separation Processes

Eung H. Cho
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Nicholas L. Abbott
Biotechnology, interfacial phenomena, colloid chemistry, soft materials, nanotechnology

Juan de Pablo
Molecular thermodynamics, statistical mechanics, polymer physics

James A. Dumesic
Kinetics and catalysis, surface chemistry

Michael D. Graham
Fluid mechanics, complex fluids, applied and computational mathematics

Charles G. Hill, Jr.
Immobilized enzyme technology, photocatalysis, kinetics and catalysis, membrane separations

Daniel J. Klingenberg
Colloid science, complex fluids, suspension rheology

Thomas F. Kuech (Chairman)
Semiconductor and advanced materials processing, solid-state and electronic materials, nanostructured materials, interface science

David M. Lynn
Polymer synthesis, biomaterials, functional materials, gene and drug delivery, controlled release, high-throughput synthesis/screening

Manos Mavrikakis
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Regina M. Murphy
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Paul F. Nealey
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Sean P. Palecek
Cellular engineering, biosensors, biochemical reaction kinetics

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Process modeling, dynamics and control, particle technology, crystallization

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Eric V. Shusta
Drug delivery, protein engineering, biopharmaceutical design

Ross E. Swaney
Process design, synthesis, modeling, and optimization

John Yin
Molecular virology, bio-informatics, pre-biotic chemistry, systems biology
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- Bioreactor Analysis
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- Environmental Catalysis
- Fuel Cells/Catalytic Reforming
- Renewable Fuels and Chemicals

**Process Analysis and Control**
- Nonlinear Process Analysis and Control
- Process Condition Monitoring, Fault Detection and Diagnosis

**Faculty**

- **Terri A. Camesano** • Ph.D., Penn State
- **William M. Clark** • Ph.D., Rice
- **Ravindra Datta** • Ph.D., U.C. Santa Barbara
- **David DiBiasio** • Ph.D., Purdue
- **Anthony G. Dixon** • Ph.D., Edinburgh
- **Nikolaos K. Kazantzis** • Ph.D., Michigan
- **Yi Hua Ma** • Sc.D., MIT
- **Fabio H. Ribeiro** • Ph.D., Stanford University
- **Robert W. Thompson** • Ph.D., Iowa State
- **Barbara E. Wyslouzil** • Ph.D., Caltech

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Csaba G. Horváth, Ph.D. Frankfurt
Michael Loewenberg, Ph.D. Cal Tech
William Mitch, Ph.D. University of California
Lisa D. Pfefferle, Ph.D. Pennsylvania
Daniel E. Rosner, Ph.D. Princeton
Paul Van Tassel, Ph.D. University of Minnesota
John Y. Walz, Ph.D. Carnegie Mellon

Adjunct Professors
• Joseph J. Pignatello
• L. Lee Wikstrom

Joint Appointments
• Thomas Graedel (School of Forestry & Environmental Studies)
• Kurt Zilm
• Donald Crothers (Chemistry)

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Enzyme Technology
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Membrane Separations
Materials Synthesis and Processing
Multiphase Transport Phenomena
Separation Science and Technology
Surface Science
BRIGHAM YOUNG UNIVERSITY
Graduate Studies in Chemical Engineering
M.S. and Ph.D. Degree Programs

Faculty and Research Interests
Calvin H. Bartholomew (Stanford) • kinetics and catalysis
Larry L. Baxter (BYU) • combustion of fossil and renewable fuels
Merrill W. Beckstead (Utah) • propellant combustion, modeling
Thomas H. Fletcher (BYU) • pyrolysis and combustion
Hugh B. Hales (MIT) • reservoir simulation
John H. Harb (Illinois) • coal combustion, electrochemical engineering
William C. Hecker (UC Berkeley) • kinetics and catalysis
John L. Oscarson (Michigan) • calorimetry and thermodynamics
William G. Pitt (Wisconsin) • materials science
Richard L. Rowley (Michigan State) • thermophysical properties
Kenneth A. Solen (Wisconsin) • biomedical engineering
Ronald E. Terry (BYU) • engineering education, reservoir engineering
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♦ Helen H. Lou (Ph.D., Wayne State University)
♦ Rafael Tadmor (Ph.D., Weizmann Institute of Science)
♦ C. L. YAWS (Ph.D., University of Houston)

RESEARCH AREAS

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♦ Heterogeneous Catalysis, Reaction Engineering
♦ Fluidization, Incineration
♦ Transport Properties, Mass Transfer, Gas-Liquid Reactions
♦ Computer-Aided Design, Henry’s Law Constant
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Process and plant design
Bruce A. Barna; Professor • PhD, New Mexico State, 1985

Demixing-polymerization, polymer materials
Gerard T. Caneba; Associate Professor • PhD, California-Berkeley, 1985

Process control, neural networks, fuzzy logic control
Tomas B. Co; Associate Professor • PhD, Massachusetts-Amherst, 1988

Chemical process safety
Daniel A. Crowl; Professor • PhD, Illinois, 1975;
Herbert Henry Dow Chair of Chemical Process Safety

Environmental reaction engineering
Jason M. Keith; Assistant Professor • PhD, University of Notre Dame, 2000

Process control, energy systems
Nam K. Kim; Associate Professor • PhD, Montana State, 1982

Polymers, composites
Julia A. King; Associate Professor • PhD, Wyoming, 1989

Polymer rheology, flow instabilities, complex fluids
Faith A. Morrison; Associate Professor • PhD, Massachusetts-Amherst, 1988

Reactor design, ceramic processing, reactor design
Michael E. Mullins; Chair and Professor, PhD, University of Rochester, 1983

Catalysis, ceramic processing, reactor design
Joseph H. Holles; Assistant Professor • PhD, University of Virginia, 2000

Environmental thermodynamics
Tony N. Rogers; Associate Professor • PhD, Michigan Tech, 1994

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David R. Shonnard; Associate Professor • PhD, California-Davis, 1991

Particulate processing, size reductions, solid waste
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Polymers, Separations, Chromatography

R.S. Artigue, D.E., Tulane
Process Control, Micro/Ultrafiltration

A. Carlson, PhD., Wisconsin, Madison
Biotechnology

D.G. Coronell, Ph.D., MIT
Kinetics, Catalysis, Materials

M.H. Hariri, Ph.D., Manchester, U.K.
Petrochemicals, Safety and Loss Prevention

D.C. Miller, Ph.D., Ohio State
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A. Serbezov, Ph.D., Rochester
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• FACULTY •

W. VICTOR CHANG
(Ph.D., Ch.E., Caltech, 1976) • Physical properties of polymers and composites; adhesion; finite element analysis

Iraj ERSHAGHI
(Ph.D., PTE, Southern Cal, 1972) • Well test analyses of fractured, geothermal, and gas storage reservoirs; reservoir characterization; petrophysical modeling

MICHAEL KEZIRIAN
(Ph.D., Ch.E., MIT, 1996) (Adjunct) • Polymer sciences; non-Newtonian fluid mechanics; interfacial transport phenomenon; chemical engineering of satellite and space sciences; kinetics of liquid propulsion and system engineering

C. TED LEE
(Ph.D., Ch.E., Texas, Austin, 2000) • Responsive surfactant systems; templated nanomaterials; protein folding; gene transfection; drug delivery; biosurfaces

CHING-AN PENG
(Ph.D., Ch.E., University of Michigan, 1995) • Algal photobioreactor, perfluorocarbon (micro)emulsion, drug and gene delivery, cellular and tissue engineering

MUHAMMAD SAHIMI
(Ph.D., Ch.E., Minneapolis, 1984) • Membrane separation; heterogeneous materials; atomistic modeling of transport and separation of fluid mixtures in nanoporous materials; flow, transport, reaction, and wave propagation in large-scale porous media; percolation theory; massively-parallel computations

RONALD SALOVEY
(Ph.D., Phys. Chem., Harvard, 1958) (Emeritus) • Physical chemistry and irradiation of polymers; characterization of elastomers and filled systems; polymer crystallization

KATHERINE S. SHING
(Ph.D., Ch.E., Cornell, 1982) • Thermodynamics and statistical mechanics; supercritical extraction; protein adsorption

THEODORE T. TSOTSIS
(Ph.D., Ch.E., Illinois, Urbana, 1978) • Chemical reaction engineering; process dynamics and control

PIN WANG
(Ph.D., Ch.E., Caltech, 2003) • Protein biosynthesis; bimolecular engineering; biomaterials engineering and microfluidic devices for biological application

YANIS C. YORTSOS
(Ph.D., Ch.E., Caltech, 1979) • Mathematical modeling of transport processes; flow and transport in porous media
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