GRADUATE EDUCATION ISSUE

COURSES ... 
Cellular Bioengineering ................................ LAUFFENBURGER
Particulate Processes ........................................ RANDOLPH
Hazardous Chemical Spills............................... KUMAR • BENNETT • GUDIVAKA
Fluid Mechanics of Suspensions ........................... DAVIS
Applied Linear Algebra ...................................... WANG
A Multidisciplinary Course in Bioengineering .......... BIENKOWSKI, SAYLER, STRANDBERG, REED

PROGRAMS ... 
Biochemical and Biomedical Engineering .................. SAN • McIntire
Hazardous Waste Management .................. KUMMLER • McMICkING • POWITZ

RESEARCH ... 
Crossdisciplinary Research: Neuron-Based Chemical Sensor Project ................. 
KISAALITA • VAN WIE • DAVIS • BARNES • FUNG • CHUN • DOGAN

and...
Good Cop/Bad Cop: Contraries in Teaching .............. FELDER
Secrets of My Success in Graduate Study ............. RAO
The Essence of Entropy ................................. KYLE
Do You Qualify for International?

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...Le Monde est à Vous!
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Editor's Note to Seniors...

This is the 21st graduate education issue published by CEE. It is distributed to chemical engineering seniors interested in and qualified for graduate school. We include articles on graduate courses, research at various universities, and departmental announcements on graduate programs. In order for you to obtain a broad idea of the nature of graduate work, we encourage you to read not only the articles in this issue, but also those in previous issues. A list of the papers from recent years follows. If you would like a copy of a previous fall issue, please write to Ray Fahien, Editor, CEE.

University of Florida
CHEMICAL ENGINEERING DIVISION ACTIVITIES

TWENTY-SEVENTH
ANNUAL LECTURESHIP AWARD TO
J.L. DUDA

The 1989 ASEE Chemical Engineering Division Lecturer is J. L. DUDA of Pennsylvania State University. The purpose of this award lecture is to recognize and encourage outstanding achievement in an important field of fundamental chemical engineering theory or practice. The 3M Company provides the financial support for this annual award.

Bestowed annually upon a distinguished engineering educator who delivers the annual lecture of the Chemical Engineering Division, the award consists of $1,000 and an engraved certificate. These were presented to Dr. Duda at a banquet during the ASEE annual meeting at the University of Nebraska.

Dr. Duda’s lecture was entitled “A Random Walk Through Porous Media,” and it will be published in a forthcoming issue of CEE.

The award is made on an annual basis, with nominations being received through February 1, 1990. Your nominations for the 1990 lectureship are invited.

CORCORAN AWARD TO
ROBERT L. KABEL

ROBERT L. KABEL (Pennsylvania State University) was the recipient of the fourth annual Corcoran Award, presented in recognition of the most outstanding paper published in Chemical Engineering Education in 1988. His paper, "Instruction in Scaleup," appeared in the summer 1988 issue of CEE.

AWARD WINNERS

A number of chemical engineering professors have been recognized for their outstanding achievements. MANFRED MORARI (California Institute of Technology) received the prestigious Curtis W. McGraw Research Award in recognition of his groundbreaking techniques for robust process control and for his innovative research on the effects of process design on the operability of chemical processes. He was cited for the practicability of his solutions and the high quality of his research contributions, which have significantly furthered engineering science, education, and industrial practice.

The William Elgin Wickenden Award, which is given to encourage excellence in scholarly writing and honors the author of the best paper published in Engineering Education during the preceding publication year, was presented to RICHARD M. FELDER (North Carolina State University).

ALAN M. LANE (University of Alabama) was the recipient of the Outstanding Zone Campus Representative Award for Zone II, in recognition of his outstanding contributions as a Zone Campus Representative from that zone.

Selected as one of only nine honorees from the entire membership of ASEE, LEWIS G. MAYFIELD (National Science Foundation) became a Fellow of ASEE.

DONALD J. KERWIN (University of Virginia) was singled out as an outstanding teacher of engineering students in the Southeastern area and was presented the AT&T Foundation Award to recognize that excellence.

Three chemical engineers were presented with the Dow Outstanding Young Faculty Award: C. STEWART SLATER (Manhattan College), BRUCE M. MCENROE (University of Kansas), and ALAN M. LANE (University of Alabama).

The Martin Award recognizing the best paper presented at the annual ASEE meeting was presented to NAM SUN WANG (University of Maryland).

NEW EXECUTIVE COMMITTEE OFFICERS

The Chemical Engineering Division officers for 1989-90 are: Chairman, WILLIAM BECKWITH (Clemson University); Past Chairman, JAMES E. STICE (University of Texas at Austin); Vice Chairman, THOMAS R. HANLEY (Florida A&M/Florida State University); Secretary-Treasurer, WALLACE B. WHITING (West Virginia University); Directors, WILLIAM L. CONGER (Virginia Polytechnic Institute) and GLENN L. SCHRADER (Iowa State University).
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WE HAVE WITNESSED a gradual change in the chemical engineering profession in the last decade. Chemical engineers have branched out and have found new and exciting career opportunities in a number of emerging areas, such as bioengineering, advanced materials processing, and electronic and photonic materials. However, nearly all of these newly emerging, high-technology areas require not only training in the fundamentals of chemical engineering, but also demand a good basic knowledge of the science in the area concerned. This is particularly true in the field of bioengineering, where much of the science was not even known ten years ago. It is our belief that if chemical engineers are to play an active and important role at the frontier of this exciting area, they must be trained to be proficient in engineering fundamentals as well as in biochemistry, cell biology, and molecular biology. Here at Rice University we are working toward this goal by forming three comprehensive research and education programs in a Biosciences/Bioengineering Institute. The Institute will be located in a new 110,000 ft² building designed for crossdisciplinary laboratory investigations involving biochemical and biomedical engineers and life scientists (see Figure 1).

FIGURE 1. Architectural model of the new Biosciences/Bioengineering Institute at Rice.
third is a joint program with the Baylor College of Medicine which leads to a MD/MS or MD/PhD degree.

The professional Master of Engineering Degree in biochemical engineering (non-thesis) is designed to provide chemical engineering students with fundamental training in biochemistry, microbiology, and molecular biology. Students enrolled in this program not only have to fulfill core requirements in chemical engineering, but also have to fulfill certain requirements offered in the Department of Biochemistry and Cell Biology, including extensive laboratory work. The five-year structure appears to be necessary to give sufficient breadth. However, students can obtain a four year Bachelors Degree if they are interested in going directly into graduate research or into a medical school option. Approximately one-third of our current chemical engineering seniors are enrolled in the biochemical engineering option.

The Doctor of Philosophy Degree in chemical engineering under the Biochemical and Biomedical Engineering program follows a philosophy similar to that of the Masters degree. Students enrolled in this program, apart from fulfilling the basic PhD requirements set forward by the Department of Chemical Engineering, are also required to take a sequence of advanced courses from the life science departments, either on campus or from the two medical schools located in the Texas Medical Center, which is adjacent to the Rice campus. Typical examples would include cell biology, molecular biology, and immunology.

The MD/MS or MD/PhD joint programs are designed to provide educational experiences of high quality leading to research careers in medicine. Successful completion of a program results in the MD from Baylor College of Medicine and the MS or PhD from Rice.

**ENHANCEMENT PROGRAM**

During the last two years, Rice University has undertaken a series of steps toward the implementation of a new plan of enhancement. This enhancement program was initiated by our president, Dr. George Rupp, in 1986, with the full support of the Board of Trustees and the faculty to “move forward to become, even more than it is today, the university its founders envisaged . . . to become an institution ‘of the first rank’.” At the research level, President Rupp has decided to focus resources on three cross-disciplinary areas in science and engineering, to move them to national recognition.

One of the three areas, which has a direct positive impact on our existing biochemical and biomedical engineering program, is the formation of a new institute: the Biosciences/Bioengineering Institute. This Institute will pool expertise from a number of engineering departments (primarily from the chemical engineering department) with the Biochemistry and Cell Biology department to solve problems that are multi-disciplinary in nature.

The main goals of the Biosciences/Bioengineering Institute are identified as: 1) to foster and strengthen collaboration among various groups at Rice which are involved in biological sciences and engineering; 2) to provide joint facilities and promote sharing of exper-

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**Ka-Yiu San** is an assistant professor at Rice University. He received his BS degree in chemical engineering from Rice University and his MS and PhD degrees from California Institute of Technology.

**Larry V. McIntire** is the E.D. Butcher Professor of Chemical and Biomedical Engineering at Rice University. He is also director of the John W. Cox Laboratory for Biomedical Engineering of the Biosciences/Bioengineering Institute of Rice. He received his BChE and MS degrees in chemical engineering from Cornell University and his PhD degree from Princeton University.
Adjunct Faculty from the Texas Medical Center

TABLE 1
Structure of Rice Biomedical Engineering Laboratory

<table>
<thead>
<tr>
<th>Staff</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Larry V. McIntire, PhD  •  Director</td>
<td></td>
</tr>
<tr>
<td>Joel L. Moake, MD  •  Associate Director</td>
<td></td>
</tr>
<tr>
<td>Anne J. Washington  •  Administrative Secretary</td>
<td></td>
</tr>
<tr>
<td>Marcella Estrellia  •  Senior Research Technician</td>
<td></td>
</tr>
<tr>
<td>Nancy Turner  •  Research Technician</td>
<td></td>
</tr>
<tr>
<td>Thomas W. Chow, PhD  •  Senior Research Associate</td>
<td></td>
</tr>
<tr>
<td>Mattias U. Noller, PhD  •  Research Associate</td>
<td></td>
</tr>
<tr>
<td>Colin B. McKay, PhD  •  Research Scientist</td>
<td></td>
</tr>
<tr>
<td>Faculty</td>
<td></td>
</tr>
<tr>
<td>C.D. Armeniades  •  Professor, Chemical Engineering</td>
<td></td>
</tr>
<tr>
<td>J.D. Hellums  •  A.J. Hartsock Professor, Chemical Engineering</td>
<td></td>
</tr>
<tr>
<td>L.V. McIntire  •  E.D. Butcher Professor and Chairman, ChE</td>
<td></td>
</tr>
<tr>
<td>M.W. Glacken  •  Assistant Professor, Chemical Engineering</td>
<td></td>
</tr>
<tr>
<td>K.Y. San  •  Assistant Professor, Chemical Engineering</td>
<td></td>
</tr>
<tr>
<td>J.V. Shanks  •  Assistant Professor, Chemical Engineering</td>
<td></td>
</tr>
<tr>
<td>J.W. Clark  •  Professor, Electrical Engineering</td>
<td></td>
</tr>
<tr>
<td>H.M. Bourland  •  Lecturer, Electrical Engineering</td>
<td></td>
</tr>
<tr>
<td>Adjunct Faculty from the Texas Medical Center</td>
<td></td>
</tr>
<tr>
<td>C.P. Alfrey, MD, PhD  •  Professor of Medicine, Division of Hematology, Baylor College of Medicine</td>
<td></td>
</tr>
<tr>
<td>S.G. Eskin, PhD  •  Associate Professor, Division of Surgery, Baylor College of Medicine</td>
<td></td>
</tr>
<tr>
<td>E.R. Hall, MD  •  Assistant Professor, Department of Medicine, University of Texas Medical School</td>
<td></td>
</tr>
<tr>
<td>E.C. Lynch, MD  •  Associate Chairman, Division of Medicine, Baylor College of Medicine</td>
<td></td>
</tr>
<tr>
<td>D.A. Sears, MD  •  Professor of Medicine, Division of Hematology, Baylor College of Medicine</td>
<td></td>
</tr>
<tr>
<td>R.T. Solis, MD  •  Associate Clinical Professor, Department of Medicine Pulmonary Division, Methodist Hospital</td>
<td></td>
</tr>
<tr>
<td>M.M. Udden, MD  •  Professor of Medicine, Division of Hematology, Baylor College of Medicine</td>
<td></td>
</tr>
<tr>
<td>K.K. Wu, MD  •  Professor and Chairman, Division of Hematology and Oncology, University of Texas Medical School</td>
<td></td>
</tr>
<tr>
<td>F.M. Yatsu, MD  •  Professor and Chairman, Division of Neurology, University of Texas Medical School</td>
<td></td>
</tr>
</tbody>
</table>

The Laboratory for Biochemical and Genetic Engineering, headed by biochemistry professor Fred Rudolph, will focus on areas such as genetics, immunology, protein engineering, molecular biology, microbiology, medicine, and agriculture. The membership of this laboratory will include faculty from various departments, including biochemistry and cell biology, chemical engineering, and chemistry (Figure 2).

The Laboratory of Basic Medical Sciences, with director George Schroepfer, has a major continuing research effort on understanding cholesterol metabolism.

As noted above, a significant part of the enhancement effort includes a new $24 million building which is being constructed to house the Biosciences/Bioengineering Research at Rice

TABLE 2

<table>
<thead>
<tr>
<th>Bioengineering Research at Rice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principal Investigators</td>
</tr>
<tr>
<td>J.D. Hellums, L.V. McIntire</td>
</tr>
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<td></td>
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<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>J.L. Moake, J.D. Hellums, L.V. McIntire</td>
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<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>L.V. McIntire</td>
</tr>
<tr>
<td>C. Armeniades</td>
</tr>
<tr>
<td>J.W. Clark</td>
</tr>
</tbody>
</table>

Bioreactor Projects

- M.W. Glacken  •  metabolic control of mammalian cell culture reactors
- K.Y. San  •  construction/characterization of new plasmid vectors
- J.V. Shanks  •  plant cell tissue culture reactors
- use of high field NMR for in vivo cell metabolism studies
engineering Institute. More than 22,000 square feet have been allocated to accommodate the chemical engineering aspects of bioengineering. This building is expected to be completed and fully operational by the winter of 1990.

CONCLUDING REMARKS

In summary, these are exciting times at Rice University. The implementation of the new enhancement program is another big step toward the goal and commitment of Rice University in striving for excellence in its undergraduate and graduate education. In particular, the formation of the Biosciences/Bioengineering Institute significantly enhances our biochemical and biomedical engineering program. It creates a unique environment which fosters close interactions between life scientists and engineers. The Institute will also serve as an effective administrative body in providing all the necessary logistical support to facilitate interdisciplinary collaboration. More importantly, the potential barriers which often arise from distant physical locations of various departments across the campus will be removed by housing life scientists and engineers under the same roof. As such, it will not only create an atmosphere which promotes interaction between the students and faculty from different disciplines, but will also provide opportunities for the engineering students to work, side by side, with life scientists from other research groups. We therefore firmly believe that our program provides a unique and challenging educational environment. Students graduating from the bioengineering program will be well-equipped with fundamental training and will have had the necessary exposure in both engineering and life sciences for further professional development.

STATE OF THE UNIVERSITY 1988-1989

To The Editor:

The following is excerpted from a larger document, "Faculty Perceptions of the State of the University, 1988-1989," which was prepared for the Faculty Senate at the University of Cincinnati. I chaired the committee which produced this report.

A university becomes too large when it can no longer provide members of the university community with the services or ambience they expect, without amassing such complicated bureaucracies that they actually end up preventing the very goals they are attempting to achieve. Steven Muller, President of Johns Hopkins has said, "The major research university of today is a radically different institution than its predecessors of three or four decades ago. The most obvious difference is size. There have now evolved in the United States between 50 and 100 major research universities that are megasize-numbering their students in tens of thousands, their faculty and administrative cadres in thousands, their buildings and their acreage in hundreds."

Most educators agree that "multiuniversity" is an apt description of the university of today. Twenty years ago Columbia University had three vice presidents and a budget of $136 million; now it has 12 and a budget of $619 million. The problem in managing such vast institutions has led to what A. Bartlett Giamatti, former President of Yale, called "the corporatization of the American university," and then wrote, "One of the great inventions of 20th century America, the private corporation, has begun to displace, as a formal structure and as a style of management, the older ecclesiastical and academic structures and styles in which universities grew up." He suggests that the "collegial" style of shared decision-making has given way to the hierarchical style of big business. While big institutions need capable administrators, "too many people see themselves as managers first, academics second. They talk about strategy, not vision. Numbers replace rhetoric. An institution that once saw itself as connected to history now prides itself as 'at the cutting edge'. The greatest subtle, unintended effect of these trends has been to split off the managers from the faculty."

If universities are becoming corporate at a time when contemporary corporations are de-layering and decentralizing, then there ought to be a symbolic lesson learned from recent corporate history. American corporate executives often have acted as a privileged class, asking sacrifices of middle management, professionals and other workers, that upper management will not make. While the rhetoric of corporate culture stresses the need to work together, the top executives stress efficiency and impose work rules and cost cutting measures. They vote themselves raises, golden parachutes and bonuses, while workers at all levels are laid off. During the recession years of 1981 to 1983, the compensation of chief executives nearly doubled while national unemployment passed the 11% mark. In symbolic contrast to these American management practices, Japanese executives in
A MULTIDISCIPLINARY COURSE IN BIOENGINEERING

PAUL R. BIENKOWSKI, GARY S. SAYLER, GERALD W. STRANDBERG, GREGORY D. REED
The University of Tennessee
Knoxville, TN 37996-2200

This course was first taught solely through the chemical engineering department (1985 thru 1987) under the quarter system and was called Microbiological Process Engineering. During semester transition the course was expanded to fifteen weeks, and a six-week laboratory was added. The course was then crosslisted in the departments of civil engineering (as an environmental course) and microbiology, and it was given a truly crossdisciplinary nature with the addition of faculty from those departments. It is presently a graduate course which is taught during the fall semester every year, and it attracts first year graduate students and some seniors from chemical engineering, environmental engineering, and engineering science and mechanics, in addition to life science graduate students from microbiology, ecology, and the Masters program in biotechnology. The course is now part of the required curriculum for the Masters program in biotechnology.

Figure 1 shows where the course (575) fits into the applied bioengineering curriculum at Tennessee. It serves as a prerequisite for courses in environmental engineering, chemical engineering, and microbiology which are offered during the spring semester. ENVR 552 is directed specifically at applications for wastewater treatment; ChE 577 addresses the development of specific models for pure cultures and their applications for producing high value biotechnology products;
Micro 670 is directed at understanding the microbial degradation and effects of toxic waste materials such as PCB's, PAH's, and TCE's. These courses all have direct applications in all three disciplines. What is required is a common starting point, and 575 meets that need. Chemical engineering seniors who take this course may elect to do an undergraduate thesis at the Center for Environmental Biotechnology during the spring semester. ChE 494 is used to give academic credit to these students for their research experience. Usually one or two students can be accommodated on center research projects each spring and/or summer.

**CHE COURSE OBJECTIVES**

The undergraduate curriculum in chemical engineering is very demanding and does not allow much room for alternate course selection by the student. Many new engineering students graduate students with research interests in bioengineering do not have sufficient background and require additional course work before they can begin their research projects. These students could rapidly advance their knowledge base in this area by working with graduate students from the life sciences (in environments like Tennessee's Center for Environmental Biotechnology) if only they could communicate effectively with the life science students, i.e., speak the language of a microbiologist. For example, there are different meanings for CSTR and chemostate, and the different way kinetic data is interpreted (the engineer's dynamic approach vs. the static approach of the life scientist). The primary objective of this course is to introduce the engineering students to bioengineering and to allow them to communicate effectively with students in the life sciences. In subsequent semesters the engineering students can develop strong backgrounds in microbiology, biochemistry, etc., by taking courses in the life sciences and by working on crossdisciplinary research projects.

CHE 575 provides the base from which to start the educational experience, it provides the basic background to start graduate research, and it feeds into more advanced biotechnology courses in several disciplines. Most engineering students have no experience in a microbiology laboratory and do not have the time or the background to take a microbiology lab. CHE 575 had a mandatory six-week laboratory which is specifically designed to give engineering students hands-on experience with the basic day-to-day laboratory problems faced by a microbiologist, such as sterilization, culture purity, analytic methods, etc. It is much easier to communicate with students and faculty in the life sciences, and to interact in crossdisciplinary research projects, if the engineering students are familiar with the problems faced by their counterparts in the life sciences. The third objective was to improve communications and to gain new insight by interacting and exchanging ideas.

**COURSE STRUCTURE**

Table 1 gives a detailed outline of the material covered in this course. Basic biochemistry and microbiology, etc., by taking courses in the life sciences and by working on crossdisciplinary research projects or doing a CHE 575 senior research project in this area.

<table>
<thead>
<tr>
<th>Period</th>
<th>Time (hrs)</th>
<th>Topic</th>
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<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>Introduction/Overview of Biotechnology</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>Biochemistry</td>
</tr>
<tr>
<td>3</td>
<td>1.5</td>
<td>Microbiology Physiology</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>Microbiology Physiology</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>Stoichiometry (mass and energy balances)</td>
</tr>
<tr>
<td>6</td>
<td>1.5</td>
<td>Enzyme Kinetics</td>
</tr>
<tr>
<td>7</td>
<td>3.0*</td>
<td>Lab #1: Basic Microbiology Techniques</td>
</tr>
<tr>
<td>8</td>
<td>3.0*</td>
<td>Enzyme Kinetics / Lab #1</td>
</tr>
<tr>
<td>9</td>
<td>3.0</td>
<td>Lab #2: Cell Growth</td>
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<td>Growth Kinetics / Lab #2</td>
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<tr>
<td>11</td>
<td>1.5</td>
<td>Reactor Analysis</td>
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<tr>
<td>12</td>
<td>1.5</td>
<td>Continuous Culture</td>
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<td>13</td>
<td>3.0</td>
<td>Lab #3: Enzyme Kinetics</td>
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<td>14</td>
<td>3.0*</td>
<td>Continuous Culture / Lab #3</td>
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<tr>
<td>15</td>
<td>3.0</td>
<td>Lab #3: Enzyme Kinetics</td>
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<td>16</td>
<td>3.0*</td>
<td>Cell/Enzyme Immobilization / Lab #3</td>
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<tr>
<td>17</td>
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<td>Lab #4: Enzyme Immobilization</td>
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<td>Lab #5: Continuous Culture</td>
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<td>Sanitary / Virology</td>
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<td>Mid Term Examination</td>
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<td>23</td>
<td>1.5</td>
<td>Molecular Biology / Recombinant DNA</td>
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<td>Biosensors</td>
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<td>Commercial Processes</td>
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<td>Biodegradation / Deterioration</td>
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<tr>
<td>30</td>
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<td>Final Examination</td>
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</table>

*Split period: 1.5 hours of lab, 1.5 hours of lecture*
ogy are covered, then reaction kinetics followed by lectures on important specialized topics in bio工程ing such as immobilization, biosensors, and re-combine DNA. The course concludes with discussions on specific applications which lead into ChE 575, ENV R 552 and MICRO 670. The text book is Elements of Environmental Engineering, by A. L. Gaudy and E. Gaudy. This book was selected because it gives good coverage of the desired material and is very readable from both an engineering and a life science standpoint (one of the authors is an engineer and the other is a microbiologist). The coverage of biochemistry and microbiology is such that an engineering student can read and understand the material with essentially no background, while the mathematics describing enzyme and growth kinetics and continuous reactors is kept on a level which can be handled by the life science students. Two faculty are present at all lectures, one from engineering and the other from the life sciences. One of the faculty will lecture and the other will be present to stimulate discussion and insure that both engineering and life science viewpoints are taken into consideration when discussing the various topics. Engineers and life scientists frequently look at the same problem from vastly different viewpoints, and combining these approaches frequently gives a better insight into the problem.

**LABORATORY**

Table 2 gives a brief description of the five experiments which comprise the laboratory. Gerald Strandberg is in charge of the laboratory and is supported by a teaching assistant from the Masters program in biotechnology. The course has the use of the biotechnology laboratory in the Walters Life Science building which is dedicated to the Masters program in biotechnology (experiments do not have to be terminated at the end of a laboratory period). The lab is conducted for six weeks, with four and one-half hours of instruction in the laboratory each week. Extra lab time is available to the students by making arrangements with the teaching assistant. Each lab group is composed of one engineering student and one life science student. Because most of the engineering students do not have experience in a microbiology laboratory, pairing them with other life science students is a most effective way for the engineering student to learn basic laboratory techniques on a one-on-one basis. At the same time the engineering student can assist his/her lab partner in designing experiments and in analysis and interpretation of the experimental data (modeling data and using models for data interpretation).

**CONCLUDING REMARKS**

This course is very effective in serving as a focal point for bringing people together from different backgrounds and in effectively and rapidly introducing engineering students to the biotechnology area. The microbiology laboratory is a unique addition to a chemical engineering course which allows both first year graduate students and seniors a hands-on experience. The course is an effective vehicle for preparing chemical engineering graduate students for research projects in the biotechnology area. It not only gives them the background to communicate with life science students in collaborating on joint research, but also prepares them for more advanced course work in this area. □
Random Thoughts...

GOOD COP/BAD COP
Embracing Contraries in Teaching

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I've come to suspect that whenever any ability is difficult
to learn and rarely performed well, it's probably because
contraries are called for—patting the head and rubbing the
belly. Thus, good writing is hard because it means trying to
be creative and critical; good teaching is hard because it
means trying to be ally and adversary of students; good
evaluation is hard because it means trying to be subjective
and objective; good intelligence is rare because it means
trying to be intuitive and logical.

So says Peter Elbow in Embracing Contraries [1],
perhaps the best book I've ever read on teaching. The
theme of the book should resonate in the minds of all
engineering professors. Most of us are often frustrated,
feeling ourselves pulled in opposite directions. We want
to be good teachers and good researchers, but don't see
how we can do both given the finite number of hours in a
day. We want to provide good educational experiences
for our graduate students, which means letting them do
some floundering and learning by experience, but we also
need to produce results quickly for our funding agencies,
which requires giving detailed directions. We want to be
good department citizens, helping carry our share of the
inevitable burden of committees, recruiting, etc., but we
also need to maximize the time we spend on the things
that get us tenure, promotions, and raises. It feels as
though we have to be both particles and waves
simultaneously, and we don't know how: we can either be
excellent particles and lousy waves, or vice versa, or do a
mediocre job of both.

Among the dilemmas inherent in our profession is
that of trying to be supportive of our students while
maintaining rigorous academic standards. I can't
improve on what Elbow has to say on the subject, so I'll
let him do most of the talking.

The two conflicting mentalities needed for good teaching
stem from the two conflicting obligations inherent in the
job: we have an obligation to students but we also have an
obligation to knowledge and society. Our loyalty to students
asks us to be their allies and hosts as we instruct and share:
to invite all students to enter in and join us as members of a
learning community—even if they have difficulty. Our
commitment to students asks us to assume they are all
smart and capable of learning, to see things through their
eyes, to help bring out their best rather than their worst when

it comes to tests and grades. By taking this inviting stance
we will help more of them learn.

But our commitment to knowledge and society asks us to
be guardians or bouncers: we must discriminate, evaluate,
test, grade, certify. We are invited to stay true to the
inherent standards of what we teach, whether or not that
stance fits the particular students before us. We have a
responsibility to society—that is, to our discipline, our
college or university, and to other learning communities of
which we are members—to see that the students we certify
really understand or can do what we teach, to see that the
grades and credits and degrees we give really have the
meaning or currency they are supposed to have.

Unfortunately, we can't play both roles simultane­ously.
Elbow's solution is to alternate between them. Start a course by spelling out requirements and
grading criteria; think about handing out a representative
final exam at the beginning of the course, with examples
of strong and weak solutions. Then,

[Having done that] I can more easily go on to...turn
around and schizophrenically start being a complete ally
of students. I have been wholehearted and enthusiastic in
making tough standards, but now I can say, "Those are the
specific criteria I will use in grading; that's what you are
up against, that's really me. But now we have most of the
semester for me to help you attain those standards, do well
on those tests and papers. They are high standards but I
suspect all of you can attain them if you work hard. I will
function as your ally. I'll be a kind of lawyer for the de­fense,
helping you bring out your best in your battles with
the other me, the prosecuting-attorney me when he emerges
at the end. And if you really think you are too poorly
prepared to do well in one semester, I can help you decide
whether to trust that negative judgment and decide now
whether to drop the course or stay and learn what you can."

Elbow suggests a number of ways to provide the
recommended support. One would be effective in small
classes or larger classes with student graders:

One of the best ways to function as ally or coach is to role­
play the enemy in a supportive setting. For example, one
can give practice tests where the grade doesn't count, or
give feedback on papers which the student can revise before
they count for credit. This gets us out of the typically
counterproductive situation where much of our
commentary on papers and exams is really justification
for the grade—or is seen that way. Our attempt to help is
experienced by students as a slap on the wrist by an
adversary for what they have done wrong. No wonder
students so often fail to heed or learn from our
Continued on page 241.
A commonly-asked question in these days of modern biotechnology is, "What is the distinction between biochemical engineering and biomedical engineering as they are traditionally understood?" Certainly, in applications this distinction still seems clear—biochemical engineering relates to the bioprocessing industry, while biomedical engineering relates to the health care industry. At the level of fundamentals, though, there is a blurring of such a demarcation. Both areas heavily involve investigation of topics in eukaryotic cell biology such as cell behavioral phenomena (e.g., growth, adhesion, differentiation, protein synthesis, and secretion), monoclonal antibodies, receptors, and gene manipulation. The major difference is that for the bioprocessing industry these topics are of interest as far as they underlie understanding of bioreactor and bioseparation performance, while for the health care industry they are of interest for their relevance to physiological function. It should be further noted that the purpose of much of the bioprocessing industry is, in fact, to provide products for use in the health care industry, completing the circle.

In making sense of the application of chemical engineering to the modern life sciences, one needs to define particular engineering subdisciplines on the basis of the particular life science disciplines to which the engineering science principles are applied. Using this view, traditional biochemical engineering has been primarily based on biochemistry and microbiology, while traditional biomedical engineering has been largely based on physiology. With the advent of the modern life science disciplines of molecular biology and cell biology, it will probably be useful to define a new engineering subdiscipline with a name something like "Molecular/Cellular Bioengineering," which is engineering applied to molecular cell biology. Chemical engineering will be the predominant engineering discipline involved, because of the fundamentally chemical nature of molecules and cells.

It may be of interest to briefly consider the historical context of this current situation. Cell biology essentially began in the 1940s with the invention of the electron microscope, which permitted intracellular structure of eukaryotic (e.g., animal) cells to be studied. Molecular biology, of course, began in the early 1950s with the discovery of the molecular nature of the genetic code. A marriage between these two, mainly in the area of animal cell biology (because of their more complex structure/function relationships), evolved in the 1970s as particular molecules involved in the cell structures responsible for cell function came to be isolated, identified, and manipulated in a reliable manner. This marriage has led to the emergence of modern cell biology, often called "molecular cell biology," in which cells—again primarily animal cells—can be studied in rigorous fashion from a molecular perspective. In the past ten years this field has achieved a position at the forefront of the life sciences in general and of biotechnology in particular. Probably every university in the country has at least one course based on textbooks like Molecular Cell Biology, by Darnell, et al., or Molecular Biology of the Cell by Alberts, et al., in its life science departments.

All of this is a preface to explain why we have begun to offer a course in chemical engineering at Penn entitled "Cellular Bioengineering." In this...
course, we deal with how chemical engineering principles can be gainfully applied to modern molecular cell biology. We focus on fundamental molecular and cellular phenomena rather than on particular applications; thus, this course is helpful to students interested in either the bioprocess industry or the health care industry, or both. Basing the material on research done primarily during the past decade, we present quantitative analyses of cell physiological phenomena in terms of the underlying principles of chemical reaction kinetics, transport phenomena, thermodynamics, and mechanics. These sorts of analyses should, in my opinion, prove to be very helpful in the coming years as knowledge of molecular bases of cellular processes needs to be synthesized into understanding the larger context of cell function.

There is a special emphasis on mammalian blood and tissue cell behavior mediated by the interaction between chemical ligands and cell receptors, which are glycoproteins typically located in the cell membrane responsible for stimulation and regulation of most important cell functions (including growth, adhesion, migration, and secretion). The reason for this is that to date there has been little treatment of this aspect of cell function by biochemical engineers relative to its prominence in molecular cell biology. One can crudely view cell function as an interplay among three key aspects. First, the genetic aspect represents what functions a cell is capable of. Only a small portion of this potential is expressed at any given point in time. Second, the enzymatic aspect represents what functions a cell is actually carrying out at a given point in time. Which functions are being carried out depends on what genes are being expressed as well as the levels of gene expression and enzyme activity. So, the missing link is what governs gene expression and enzyme activity. Although all of this is oversimplification for purposes of clarity, to a large extent gene expression and enzyme activity are regulated by intracellular signals generated by ligand/receptor binding interactions. Receptors basically possess two central properties: they are capable of selective binding to specific chemical ligands and they are capable of transducing this binding event into intracellular biochemical signals. These signals then lead to regulation of gene expression and enzyme activity.

Most chemical engineering departments, including our own, currently offer biochemical engineering courses that treat enzyme reactions and gene expression from chemical reaction engineering and transport phenomena perspectives, so it is this third aspect of cell regulation and resulting cell function that requires additional attention.

In this course . . . we focus on fundamental molecular and cellular phenomena rather than on particular applications . . . thus (the course) is helpful to students interested in either the bioprocess industry or the health care industry, or both.

The outline currently used is as follows:

I. Receptor-Ligand Binding and Signal Transduction
   A. Monovalent binding and apparent cooperativity effects
   B. Multivalent binding and crosslinking
   C. Transport limitations
   D. Probabilistic considerations
   E. Signal transduction and second messengers

II. Intracellular Protein Trafficking
   A. Endocytosis
   B. Intracellular sorting
   C. Protein synthesis and secretion

III. Cell Proliferation
   A. Cell cycle kinetics
   B. Growth factor regulation
   C. Cell density effects

IV. Cell Adhesion
   A. Thermodynamic models
   B. Mechanical models
   C. Dynamical models

V. Cell Migration
   A. Cell population behavior
   B. Individual cell behavior
   C. Mechanistic models

There is no required text for this course, but the previously mentioned molecular cell biology texts are referred to often for background reading. More specific readings in the research literature, frequently including recent comprehensive review articles as well as original research papers, are regularly assigned. Problem sets are also distributed weekly, allowing the student to work out examples of mathematical models and analyses of the various phenomena considered in class. Most importantly, there is a term project in which the student is asked to develop his or her own original mathematical model for a phenomenon of personal interest, and to apply an analysis of this model to relevant experimental data in the literature.

In order to provide a better picture of the course contents I will now go on to present a brief overview of the various topics covered, based on the key literature read and discussed in class. To begin with, a broad foundation of background reading in Darnell, et al., or Alberts, et al., is assigned, including chapters 1, 5, 6, 7, 14, and 15 in the former, or chapters 1, 4, 6, 7, and 10 in the latter. Most of this material is dealt with in detail later, but some of the early chapters are
necessary for the student to put particular phenomena into overall context.

The first section of the course looks at fundamentals of receptor/ligand binding and signal transduction processes. Good background, especially on common experimental techniques and typical pitfalls, is provided by chapters three through six in a book by Limburd entitled Cell Surface Receptors: A Short Course on Theory and Methods. The relevant portions of the basic texts are chapters 15 and 16 in Darnell, et al., and chapter 13 in Alberts, et al. Simple monovalent receptor and ligand binding equilibrium and kinetic properties are a good place to start, for much of the mathematical analysis is reminiscent of enzyme kinetics, quite familiar to many chemical engineering students. The well-known equilibrium Scatchard plot is introduced, a plot of the ratio of bound ligand to free ligand versus bound ligand, with consequent simple determination of binding equilibrium constant and receptor number from the slope and ordinate-intercept. Complications inherent in correct interpretation of this plot are immediately presented, as described nicely by Limburd's book and in some papers by Klotz [1] which include improper consideration of nonspecific ligand binding, neglect of ligand depletion, and lack of data at sufficiently high ligand concentration. Modern numerical parameter estimation methods can sometimes be gainfully applied, as described by Munson and Rodbard [2], Munson [3-4] and DeLeon, et al. [5]. The latter paper helpfully discusses limitations of these methods, using computer simulation comparisons. Of course, more fundamental complications frequently arise from the presence of other effects, including multiple receptor or ligand subpopulations (especially with radioactively or fluorescently labeled ligand), multivalency (allowing possible cooperativity effects), and additional receptor processes such as aggregation, internalization, and covalent modification, which may all result upon ligand binding. These various phenomena generally result in apparent changes in binding affinity with ligand concentration, often referred to as cooperativity. Examples and corresponding analyses of these can be found in the literature. As examples, the following papers are useful references: receptor subpopulations, Smith [6]; covalent modification, deWit and Bulgakov [7]; aggregation in ternary complexes, Gex-Fabry and DeLisi [8]; and affinity conversion, Lipkin, et al. [9]. Cell surface aggregation effects, especially when multivalent receptors and ligands are involved, can lead to a variety of complications, and also appear to be central to many signal transduction processes. Good example references in this area from a vast literature can include DeLisi and Chabay [10], Perelson and DeLisi [11], and Dembo and Goldstein [12].

In all of these analyses, reaction rates of receptor/ligand binding and dissociation are central. It is not surprising to chemical engineers that often these rates can be transport-limited. In these sorts of situations involving a finite number of discrete receptor sites spatially distributed on the cell surface, transport limitations can lead to unanticipated effects. The seminal paper in this area is by Berg and Purcell [13] which demonstrates the nonlinear dependence of overall binding and dissociation rate constants on the receptor surface density. Improved mathematical treatments have followed, such as DeLisi and Wiegel [14], Brunn [15], and Shoup and Szabo [16], permitting generalization to more complicated situations. The key result, however, is that the rate constants for binding or dissociation per receptor can not be calculated simply by dividing the rates on a per cell basis by the receptor density when ligand diffusion is rate-limiting. Transport limitations can also lead to false indications of cooperative binding phenomena. A very interesting example of this is given by Wiley [17]. Although ligand diffusion in free solution to the cell surface is often not rate-limiting for receptor/ligand binding, receptor diffusion within the cell membrane is generally rate-limiting for receptor aggregation. Good treatments of this include Goldstein, et al. [18] and Keizer, et al. [19].

An interesting consideration not typically relevant to chemical engineering problems is that of probabilistic effects. That is, most chemical reaction models assume deterministic behavior due to statistical averaging over very large numbers of molecules. Since receptor densities are usually in the range of $10^8$ to $10^9$ per cell, since behavioral responses can depend on amplification of exceedingly small signals, and since experimental observations are often made on the basis of small numbers of cells or even individual cells, signal noise can be quite significant and is sometimes the key to proper understanding of the behavior. Mathematical discussions of this aspect can be found in Berg and Purcell [13], and in DeLisi, et al. [20] and Lauffenburger and DeLisi [21]. Stimulating cell biological examples in which it is relevant include inheritance of behavior-regulating proteins [22], cytoskeletal assembly [23], and cell migration [24,25]. An extremely helpful source of fundamental mathematical concepts here is the book by Gardiner, Handbook of Stochastic Methods.

There is not much analysis available on signal transduction events following receptor/ligand binding. The most heavily studied system is that of the so-called
“G-proteins” and cyclic AMP generation as an intracellular second messenger. Useful examples detailing mathematical models and analysis of quantitative experimental data include Higashijima, et al. [26] and Rapp, et al. [27].

The second section of the course deals with reaction and transport processes involving cell receptors and other proteins beyond cell surface events. These “trafficking” processes include internalization of receptors and receptor/ligand complexes, sorting of these molecules in intracellular organelles—with consequent recycling of some to the cell surface and degradation of others intracellularly, and synthesis and secretion of proteins through intracellular routes. In addition to the Darnell, et al., and Alberts, et al., background, good review articles exist: Steinman, et al. [28] and Wiley [29] are among the best. The latter, in fact, provides a good mathematical modeling treatment along with biological basics. Trafficking processes can have a dramatic influence on both receptor/ligand binding dynamics and on signal transduction and behavioral responses. Biological examples of these consequences can be found in Wiley and Cunningham [30], Zigmond, et al. [31], and Myers, et al. [32], with more general mathematical analyses in Gex-Fabry and DeLisi [33] and Beek and Goren [34]. A major implication is that at temperatures allowing trafficking processes, receptor/ligand binding dynamics cannot be interpreted simply using Scatchard plot methods. Although the biochemical mechanisms are only now emerging, possibly helpful models and analyses of the crucial intracellular sorting step have been presented [35, 36]. Finally, it is becoming clear that the trafficking mechanisms involved in protein synthesis and secretion in eukaryotic cells are likely to be quite similar to those involved in endocytic protein uptake. There is no mathematical analysis of this process available to date, but a suggestive recent review of experimental observations is given by Burgess and Kelly [37].

With this understanding of fundamental receptor/ligand processes, one can move on to analysis of resulting cell behavioral phenomena. In this course, we focus on three: proliferation, adhesion, and migration, although there are others presently not as well studied, such as secretion and differentiation. These three phenomena comprise the next three sections of the course.

In the area of cell proliferation, the background in Darnell, et al., is pages 147-154, 192-200, 517-524, and 1035-1046, and in Alberts, et al., is Chapter 11. An excellent reference text is Baserga, *The Biology of Cell Reproduction*. The focus of our presentation is the regulation of cell proliferation by receptor-mediated growth factor signals, with a good recent review provided by Deuel [38]. To begin this section, however, context is provided by some discussion of more general models for cell cycle kinetics such as Takahashi [39], Fried [40], and Aroesty, et al. [41]. A good reference for this sort of model is by Swan, *Some Current Mathematical Topics in Cancer Research*, and a useful review can be found in Bertuzzi, et al. [42]. Useful background information on nutrient effects on mammalian cell proliferation kinetics can be found in McKeehan and McKeehan [43], and some recent quantitative work is also available on this subject [44, 45]. A fairly rigorous analysis, distinguishing effects on the cycling rate of proliferating cells from those on the fraction of cells proliferating, can be found in Cowan and Morris [46]. It seems that it is more likely that the latter quantity is typically growth rate-controlling, as the cycling rate of proliferating cells is fairly constant. Effects of growth factor binding and trafficking on overall proliferation rate is a crucial topic, one of great current activity. A superb starting point is the work by Knauer, et al. [47], who were able to demonstrate a linear dependence of cell proliferation rate on the steady-state number of growth factor/receptor complexes for human fibroblasts responding to epidermal growth factor. Further effects of trafficking on the degree of proliferative responsiveness have been analyzed by Lauffenburger, et al. [48], indicating that there may be an important relationship. Although there is little additional work along these lines available to date, it is a major premise of this course that understanding of cell proliferation phenomena, probably including most empirically observed effects like serum requirements, attachment requirements, contact inhibition, and inoculum cell density requirements, will require quantitative analysis of receptor-mediated behavior. One example of this is the interpretation of cell inoculum density requirements in terms of possible autocrine (self-released) growth factors [49], and more can be expected to come along in the near future. A couple of noteworthy papers not directly concerned with growth factor regulation, but providing related important models of eukaryotic cell proliferation, are Alt and Tyson [50] and Cherry and Papoutsakis [51]. The first paper deals with probabilistic aspects of a critical cell cycle regulatory species in yeast growth, which in many ways is a good model system for intracellular control mechanisms of mammalian cell growth. The second paper shows how simple geometric considerations can influence net cell population growth on surfaces when proliferation is “contact-inhibited.”
In the area of cell adhesion, appropriate background reading on receptor aspects are reviews by Yamada [52] and by Buck and Horwitz [53]. A seminal paper laying out the biophysical fundamentals is that by Bell [54]. There are two central underlying issues for engineering analysis. One is how to model a receptor/ligand bond, especially in regard to the effects of mechanical stress on its kinetic and equilibrium properties. Another is how the variety of forces present act on cell mechanical properties to yield a contact area, within which the two surfaces are in sufficiently close contact to permit receptor/ligand bonds to form. Most analytical efforts are based in some manner on Bell’s concepts and can be divided into two major categories: equilibrium models and dynamic models. In the first category there are additionally two chief types, mechanical and thermodynamic. A large number of papers based on equilibrium thermodynamic models have been published; good representatives are Bell [55], Bell, et al. [56], and Torney, et al. [57]. The mechanical models are principally by Evans [58]. Both of these types of models attempt to predict the strength of equilibrium adhesion, with the primary goal of determining influence of various system parameters on the force required to detach a cell adhered to a surface or another cell. (It should be mentioned that there is a vast literature on cell adhesion based on surface energy ideas, a recent example being by van Oss [59]. However, these do not easily incorporate specific biochemical receptor/ligand effects and so are largely neglected in this course). There has been much less work to date on dynamical models, exceptions being Hammer and Lauffenburger [60] and Dembo, et al. [61]. The former deals with kinetics of a cell encountering a potentially-adhesive surface in the presence of fluid shear flow, and attempts to predict the conditions under which adhesion will occur. The latter focuses on the dynamic behavior of a cell maintained near such a surface, with the chief result being prediction of a steady-state cell rolling velocity in fluid shear flow. As mentioned earlier, an important aspect of cell adhesion is the cell mechanical properties; a helpful reference on this topic is by Dong, et al. [62].

Good background reading on the topic of cell migration can be found in books by Lackie (Cell Movement and Cell Behavior), Trinkaus (Cells into Organs: The Forces that Shape the Embryo), and Wilkinson (Chemotaxis and Inflammation). Three major aspects are treated in this course. The first topic is the development of mathematical models for cell population migration behavior, including chemotaxis. There is a substantial literature in this area, with the following being the most significant papers: Patlack [63], Keller and Segel [64], Alt [65], Lauffenburger [66], and Othmer, et al. [67]. These provide cell flux expressions analogous to diffusion/convexion equations for molecular transport, and relate cell population transport parameters (the random motility coefficient and chemotaxis coefficient) to fundamental individual cell parameters (speed, persistence time, directional bias). These expressions can be used to analyze cell migration experimental assays for determination of the values of the population parameters, as in Tranquillo, et al. [68] and Buettner, et al. [69]. The second topic is analysis of individual cell paths for quantification of the fundamental parameters. The central papers in this area are Nossal and Zigmond [70], Dunn [71], Dunn and Brown [72] and Othmer, et al. [73]. The last topic is an especially timely and difficult issue—the biochemical/biophysical mechanisms underlying cell migration. Useful biological reviews are Bretscher [74] and Singer and Kupfer [75] on membrane and cytoplasmic processes, and Devreotes and Zigmond [76] on chemosensory processes. Important basic information on cell-generated forces can be found in Harris [77]. Concerning mathematical models of these phenomena, there are a number of efforts toward analysis of the rate of pseudopodal extension, which is the first step in locomotion. Among these are Oster and Perelson [78], and Zhu and Skalak [79]. The former emphasizes hydrostatic and osmotic forces in generating membrane protrusion and cytoplasmic flow, while the latter focuses on cytoskeletal assembly. Insufficient information exists to definitively distinguish between these two hypotheses, although circumstantial data demonstrating influence of extracellular osmotic levels on membrane protrusions favor the former at this point. Oster [80] provides an extremely useful discussion of the various forces involved, including membrane mechanics, but without mathematical analysis. An insightful model relating overall cell locomotion rate to receptor distribution along the cell membrane is by Dembo, et al. [81]. This model does not, however, attempt to predict movement speed from cell-generated forces, a most daunting but important goal. An extremely crude preliminary attempt at doing just this is offered by Lauffenburger [82]. Finally, Tranquillo, et al. [83] provides a model not for the rate of locomotion, but for the direction, based on a simple model of receptor-mediated signal transduction including probabilistic effects. This model successfully predicts cell paths in the presence and absence of chemical attractant concentration gradients.

If time permits, which it probably will not, one can
go on to discuss papers which incorporate these sorts of models for fundamental cell behavioral phenomena into analyses of physiological phenomena. There is a vast literature on models of the immune response (see, for example, Perelson [ed.], *Theoretical Immunology*). Other interesting and important processes which have received less extensive analysis to date include angiogenesis [84] and wound healing [85].

This article has been an attempt to provide a superficial overview of topics that can be profitably treated from the perspective of chemical engineering applied to modern molecular cell biology, along with some key references to guide the treatment. There is no question that this field will both grow and change tremendously over the next few years, but I hope that this article will be of some help to anyone wishing to study in this area.

Finally, I would like to express my gratitude to a number of students who have been of substantial help in teaching this course: Helen Buettner, Paul DiMilla, Daniel Hammer, Jennifer Linderman, Bob Tranquillo, Cynthia Starbuck, and Flaura Winston. Their participation and special insights have made this an exceptionally stimulating course.

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55. Bell, *Cell Biophys.*, 1, 133 (1979)
A USEFUL WORKING definition for particles [1] is, "that state of subdivision of matter whose shape depends on the process by which it was formed and on the intermolecular cohesive forces present." This definition applies equally well for liquid droplets (spherical, maintained by surface tension) or crystalline solids having a geometric shape (e.g., cube, platelet, etc.) consistent with the crystalline structure and affected by the local molecular environment producing the crystal.

This article describes a special topics graduate course (ChE-514) on particulate processes given frequently by the author at the University of Arizona. The text for the course is Theory of Particulate Processes: Analysis and Techniques of Continuous Crystallization [2]. The subtitle has been said to be more accurate in describing the book than the title, although the second edition attempts to correct this impression. The text was motivated by the necessity of collecting and organizing all the information on the Crystal Size Distribution (CSD) problem, which is covered extensively in the course Particulate Processes. Thus, the course and text are nearly inseparable. ChE-514 is a "required" course for the writer's students who are engaged in process crystallization research. The course is given whenever the combination of graduate students needing to take it (ADR’s) plus other graduate students desiring additional chemical engineering credit to fill out their graduate study program, exceeds the minimum class enrollment for a graduate offering. The course unashamedly concentrates on process crystallization (and CSD) as the example par excellence to illustrate the predictive population balance theory of particulate processes formally developed in the text. The writer attempts to maintain a reasonable balance of non-crystallization topics considering the background of those enrolled.

COURSE OUTLINE

Table 1 shows the subject outline of Particulate Processes. It is identical to the text with the exception of Chapter 10 (in the course, the last periods are used for student reviews of the current literature of particulates). The ground rules are that crystallization students cannot choose a crystallization article to review, while others may. The main point is that the articles must emphasize the distributed nature of particulate systems. Proposed titles are thus pre-screened. Five minutes of perusing the article to be reviewed can immediately determine if the course has been a success.

One graduate student suggested that scarce semester-end time could be saved if written, rather than oral, critiques were handed in as a term project. This is an excellent idea except, of course, that it shifts a major work load from the student to the in-
In addition to emphasizing the distributed nature of particulates, the course emphasizes predictive rather than descriptive modeling of the particle distribution using population balance mechanics. An illustration of CSD prediction and manipulation will be presented for the useful double draw-off (DDO) configuration.

In addition to emphasizing the distributed nature of particulates, the course emphasizes predictive rather than descriptive modeling of the particle distribution using population balance mechanics. An illustration of CSD prediction and manipulation will be presented for the useful double draw-off (DDO) configuration. Current unit operation texts [3] now present the CSD from a Mixed Suspension, Mixed Product Removal (MSMPR) crystallizer in a predictive context, but stop short of CSD manipulation (which would require crystallization kinetics). The first two chapters (and course topics) describe the general nature and elementary statistics of distributed particulates (e.g., means, variance, cumulative vs. density, etc.). The distributions are presented in density form. (Students often have trouble with the units of population density, (length)$^{-3}$). Much attention is given to the gamma distribution (the natural distribution of crystallization processes), but other useful empirical distributions, e.g., Rosin-Rammler and Gaudin-Melloy, that are routinely used in the minerals industry [4] are presented in the course.

Chapter 3 develops and formalizes the multi-variate population balance which is used predictively throughout the remainder of the course. At this point, the useful moment transformation is introduced. The leading moments of the population density function

$$m_j = \int_0^\infty L^j n(L) dL$$

form a closed set of non-linear algebraic equations which, in principle, completely describe the idealized MSMPR crystallizer, given the nucleation/growth rate kinetics of a particular system. Roughly speaking, the MSMPR concept is to crystallization as the CSTR is to reaction engineering with the advantage that the form of the equations is kinetics-independent. Thus, for a specific case the kinetics can be brought in as auxiliary equations to complete the solution.

Chapter 4 develops the MSMPR concept in detail. This chapter, together with Chapters 7 (CSD manipulation) and 8 (CSD dynamics), form the core of presentations for the industrial short course. Chapter 5 presents crystallization mechanisms and kinetics from an elementary level. The writer often suffers from acute Felder's Impostor Syndrome [5] when discussing crystal nucleation and growth mechanisms. This subject could better be covered by someone in material sciences well-versed in crystallography. For example, when discussing crystal growth mechanisms by spiral dislocations, the writer finds that even the most imaginative students are barely convinced that the crystal dislocation is self-perpetuating. Crystal nucleation/growth kinetics can often be described for high yield systems with simple power-law empiricisms of the form

$$B^* = k_N G^i M_T^j$$

where $i$ and $j$ are two parameters respectively describing

Continued on page 227.
A course in...

HAZARDOUS CHEMICAL SPILLS

Use of the CAMEO Air Dispersion Model to Predict Evacuation Distances

ASHOK KUMAR, GARY F. BENNETT, VENKATA V. GUDIVAKA
The University of Toledo
Toledo, OH 43606

The University of Toledo offers several air pollution courses taught by the senior authors to engineering undergraduate and graduate students. In the undergraduate courses, “Introduction to Air Pollution Engineering” and “Air Pollution Control,” the students are exposed to the concept of air dispersion modeling. The training in dispersion modeling continues in two senior/graduate courses: 1) “Dispersion Modeling” and 2) “Hazardous Chemical Spills.”

This paper provides an overview of the CAMEO model [1] and its uses in the classroom as a training tool in the “Hazardous Chemical Spills” course. The model can be obtained from the National Oceanic and Atmospheric Administration, Hazardous Materials Response Branch, 7600 Sand Point Way NE, BIN C15700, Seattle, Washington 98115.

Chemical accidents are an unfortunate reality of industrial society. With billions of pounds of toxic chemicals being produced, stored, shipped, and used daily, it is axiomatic that leaks, spills, and accidents will occur. The consequences of these chemical spills can range from a simple nuisance to virtual destruction of a body of water or to thousands of deaths and injuries.

In the early days of spill technology and response (the 1970s), the major concern in dealing with chemical spills was for pollution of the aquatic environment. Indeed, spill response and cleanup efforts were initially directed only at oil spills, but soon chemical spills and the destruction they caused in the aquatic environment surpassed concern for the impact of oil on the ecology. Two early examples of chemical spills are the destruction of Shawnee Lake in Ohio [2] by a gallon of strychnine-treated corn mixed with endrin, and the intentional discharge of hexachlorocyclopentadiene into the sewers of Louisville, Kentucky. These spills severely impacted major bodies of water [3]. Subsequently, Louisville suffered a more serious incident when hexane that was discharged into the sewer system, vaporized and exploded, causing thousands of dollars of damage.

As serious as the environmental impact of chemicals on water resources is, it is those spills (or incidents) that result in emissions of toxic (volatile) chemicals into the air that pose the greatest danger to both first responders and nearby residents. Clearly the most dramatic and devastating chemical incident that has ever occurred was the release of 30 to 35 tons of methyl isocyanate at Bhopal, India, on December 3, 1984. This toxic chemical release killed an estimated 2,500 people and injured over 200,000 more [4].

Fortunately, extremely toxic chemicals such as methyl isocyanate are produced in limited amounts at

Gary F. Bennett received his BSc from Queen’s University and his MS and PhD degrees from Michigan, all in chemical engineering. He has taught at The University of Toledo since 1963 and started a course there in hazardous chemical spills ten years ago. He is consultant to the Toledo fire division on chemical spills, has written several spill prevention and control plans for industry, and is author of the Hazardous Spills Handbook, published by McGraw Hill.

Ashok Kumar is a professor of civil engineering at The University of Toledo where he teaches courses on air pollution and conducts research in the area of air pollution modeling and monitoring. He received his BS from Aligarh University in India, his MS from the University of Ottawa, and his Doctoral Degree from the University of Waterloo. A registered professional engineer, he is a consultant to industrial organizations.
very few locations in the world. But other toxic gases such as ammonia, chlorine, and hydrochloric acid are widely used and have been released all too frequently. Moreover, billions of pounds of these chemicals are produced every year, and their storage and use are ubiquitous. Notable spills involving these compounds include:

**Ammonia** • Houston, Texas: Tanker accident; 1.9 tons of ammonia released with a 30 m high cloud formed with danger persisting for two and one-half hours [5].

**Chlorine** • Mississauga, Toronto, Canada: Railroad derailment; 27 tons of chlorine released in a fire; 300,000 people evacuated over an area of 129 km² [6].

**Silicone Tetrachlorida** • A storage tank released 1100 m³ (284,000 gal) of SiCl₄ over five days; HCl vapor was formed when the SiCl₄ contacted moisture in the air; 160 people were hospitalized, 16,000 were evacuated, and the toxic cloud extended 8 to 16 km from the tank [7].

**Nitric Acid** • A puncture in a rail tank car released 55 m³ (14,000 gal) of 99% solution of nitric acid; the resulting vapor cloud of toxic nitrogen dioxide forced the evacuation of 5,000 people [9].

**Pesticides** • Fires at facilities storing pesticides and/or hazardous waste have sent toxic gases wafting across the landscape to threaten anyone in their way. Fumes from a 1974 pesticide fire in Alliance, Ohio, caused fire personnel and residents to exhibit symptoms that included nausea, burning eyes and throats, and dizziness [8].

**Transportation Accidents** • Transportation accidents such as the ones involving chlorine in Canada [6] and white phosphorus at Miamisburg, Ohio [10], in 1987 with a resulting fire that threatened nearby residents. In Miamisburg, a railroad car of white phosphorus burned and released a toxic cloud of combustion products that caused a mass evacuation of nearby residents.

In all cases of releases of volatile toxic chemicals, whether or not a fire is involved, air dispersion modeling is of great assistance to the first responder. Indeed, dispersion modeling is essential in predicting areas that should be evacuated. Without such modeling, the evacuation area could not be calculated at all; it could only be "guess-timated." Consequently, without the calculation tools given by air dispersion modeling, the On-Scene Commander either under- or over-estimates the evacuation zone. Under-estimating the evacuation zone leaves people in danger; over-estimating needlessly moves people and constitutes a hazard of a different kind, especially to the sick and elderly who are negatively impacted by the move and concomitant disruption.

**STUDENT MODELING PROGRAM**

Environmental engineering students at the University of Toledo solve air dispersion problems by using computer models based on known theoretical concepts. The computer models are chosen from programs available in the public domain and include modeling programs used by regulatory bodies in both the United States and Canada.

One model chosen for this course is the CAMEO model which has been developed by the National Oceanic and Atmospheric Administration. The model performs a variety of calculations for a chemical spill, and in the classroom the CAMEO Air Model can be used for several purposes: 1) to develop an intuitive feeling for the importance of different variables related to the toxic releases and to test "what-if" type questions, 2) to compute the maximum ground level chemical concentration resulting from a spill, 3) to map hazard zones for evacuation purposes, and 4) to perform sensitivity analysis using varying chemical and toxicological inputs, source data, and meteorological information.

Additionally, all the features included in the model are useful in various contingency planning and response activities where it is necessary to compute the downwind concentrations as a function of distance resulting from a hypothesized release of a toxic volatile material.

**THE CAMEO SYSTEM**

An explanation of the CAMEO system, one of the commercially available air dispersion model programs, is given to the students. The level of discussion conducted in the classroom, however, depends on the course. The students are told that CAMEO has the following features for calculating downwind chemical concentration from release:

1. A basic Gaussian algorithm is used with either a continuous or instantaneous release configuration.

2. The atmospheric data can be inputted directly by the user or obtained from a remote meteorological station.

3. A chemical library is available; this library contains the toxicological, chemical, and thermodynamic parameters necessary to derive various source strength estimates and relate the pollutant distribution patterns to human health effects.
4. The source strength estimates can be entered directly in English or metric units; however, the program can calculate the effective source strength from an exposed pool of spilled chemical, given the chemical identity and the surface area of the pool.

5. The system has the ability to store a map using digitization.

6. A variety of graphic or tabular options can be displayed on the screen or sent to the printer; the system also has the ability to clip screen images to a file that can be overlaid on maps that are available in other parts of the system.

Since the CAMEO system uses the well-known Gaussian dispersion model, a brief discussion points out the limitations of the model as follows: 1) typical errors can be as high as a factor of two, and 2) greater errors can result from spills during low wind speed and very stable atmospheric conditions than at high wind speed.

It should be noted that the CAMEO model does not take into account terrain effects and the impact of building wakes. Also, heavy gas effects are not included. Moreover, the model results apply only to the selected chemicals; fire by-products or other chemical transformations can be entered into the system by the user as separate chemicals.

HOW TO USE THE CAMEO MODEL

The students are instructed to use the CAMEO program installed on an Apple Macintosh computer. They are told about the menu options in the CAMEO program and are informed that the best way to run the program is to use the following order for menu options: 1) select a chemical from the chemical option, 2) set the atmospheric options (either by the meteorological station or user input), 3) set the source strength of the spill, and 4) run the model by selecting the continuous or puff option from the option menu.

EXAMPLES OF CLASSROOM EXERCISES

Six problems have been selected to illustrate classroom use of CAMEO. These six problems, when used in a course, enable a student to become familiar with some of the many uses of the CAMEO Air Model. The problems selected utilize most of the facilities offered by the demonstration program model.

The student is advised to try to solve the problems using the CAMEO program and to compare his results with those given by the instructors. The student is advised to try solving different problems given in air pollution textbooks with this model in order to gain familiarity with its applications.

The problems are based on "real-world" spill situations found in the literature. Problems 1 and 2 are modified from reference 11; problem 3 is from reference 12; problem 4 is from reference 13; problem 5 is from reference 14; and problem 6 is from reference 15.

Problem 1

Ammonia was released at a rate of 6050 g/sec for 30 min. The ambient wind speed at the time of release was 2 mi/hr (3.2 km/hr), and the wind was blowing from 350°. The atmospheric stability was "unstable" (A), and the ambient temperature was 28°C. Assume an inversion height of 1500 ft (457 m). Use the CAMEO Air Model for a continuous source and determine the downwind IDLH* and TLV-TWA* distances and travel times to reach those distances.

Locate the source at the chemical facility near South Chicago Street on Map E13 or F13 and plot the IDLH and TLV-TWA hazard zones (see Figures 1 and 2).

*IDLH defines the concentration of a chemical "Immediately Dangerous to the Life and Health" if someone is exposed. TLV is the "Threshold Limit Value" concentration which is the accepted safe concentration for 8-hr/day exposure of workers over their working life. TWA is the "Time Weighted Average" of the concentration.

### TABLE 1
Input Data for Six Chemical Spills

<table>
<thead>
<tr>
<th>Problem #1</th>
<th>Problem #2</th>
<th>Problem #3</th>
<th>Problem #4</th>
<th>Problem #5</th>
<th>Problem #6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of Chemical Selected</td>
<td>Ammonia Solution</td>
<td>Hydrogen Sulphide</td>
<td>Nitric Acid</td>
<td>Chlorine</td>
<td>Methyl Isocyanate</td>
</tr>
<tr>
<td>Atmospheric Stability Class</td>
<td>A</td>
<td>D</td>
<td>E</td>
<td>D</td>
<td>F</td>
</tr>
<tr>
<td>Inversion Height (ft)</td>
<td>1500</td>
<td>600</td>
<td>500</td>
<td>600</td>
<td>650</td>
</tr>
<tr>
<td>Wind Speed (mi/hr)</td>
<td>2</td>
<td>5</td>
<td>4.7</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Wind Direction</td>
<td>350</td>
<td>350</td>
<td>315</td>
<td>90</td>
<td>310</td>
</tr>
<tr>
<td>Ambient Air Temperature(°C)</td>
<td>28</td>
<td>28</td>
<td>20</td>
<td>20</td>
<td>17.5</td>
</tr>
<tr>
<td>Average Ground Roughness</td>
<td>City Center</td>
<td>Very Smooth</td>
<td>Thick Grass</td>
<td>Lawn</td>
<td>City Center</td>
</tr>
<tr>
<td>Source Strength</td>
<td>6050 g/s</td>
<td>72,000 g</td>
<td>66,000 g/s</td>
<td>11,340 g/s</td>
<td>7,400 g/s</td>
</tr>
<tr>
<td>Exit Velocity (ft/sec)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

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Problem 2
A pipeline of a gas processing facility ruptured and released 72,000 g of H₂S. The ambient wind speed was 5 mi/hr (8 km/hr), and the wind was from 350°. The atmospheric stability was neutral (D), and the ambient air temperature was 28°C. Assume an inversion height of 600 ft (183 m).

Assume an instantaneous release and determine the downwind IDLH and TLV-TWA distances and travel times. Locate the source at the chemical facility of South Chicago Street on Map E13 or F13, and plot the IDLH and TLV-TWA vapor hazard zones (see Figures 1 and 2).

Problem 3
During the night, at about 2 a.m., 20 tons (20 x 10⁶ g) of fuming nitric acid were spilled on flat ground. At 2:05 a.m. the temperature was 20°C, and the wind was from the northwest (315°) at 4.7 mi/hr (7.5 km/hr). Assume an atmospheric stability of (E) and an inversion height of 500 ft (152 m). Assume a continuous source (66,000 g/sec).

Compute the downwind IDLH and TLV distances and travel times. Plot these contours on the map and make recommendations about the extent of the evacuation zone.

Problem 4
A continuous release of chlorine at a rate of 11,340 g/sec occurs at a chemical plant. The atmospheric conditions at the time are neutral (D). The ambient wind speed is 10 mi/hr (16 km/hr) and the wind is blowing from the west. The ambient air temperature is 20°C.

Assume a mixing height of 600 ft (183 m). Assuming a continuous source (66,000 g/sec).

Compute the downwind IDLH and TLV distances and travel times. Plot these contours on the map and make recommendations about the extent of the evacuation zone.

Problem 5
In a disaster at a pesticide plant in India, 40 tons (40 x 10⁶ g) of methyl isocyanate were released in 90 minutes (7400 g/sec) at 12:30 a.m. when the ambient temperature was 17.5°C.

The ambient wind speed was 9 mi/hr (14 km/hr) and the wind was from 310°. The mixing height at that time was about 650 ft (198 m). The conditions were said to be very stable, and a stability class of (F) may be assumed. Compute the TLV and IDLH travel times and distances; plot the TLV and IDLH hazard zones.

Problem 6
100,000 gal of toluene were spilled as a result of a pipeline rupture in Ohio. The time was 10 p.m. and the ambient temperature was 10°C. The wind speed was 3 mi/hr (4.8 km/hr) and the conditions were neutral (D Stability). The mixing height was 600 ft (183 m). Use the puddle model to determine the TLV and IDLH distances and travel times. Assume a puddle area of 1000 ft² (93 m²) and an exit velocity of 1 ft/sec (0.3 m/sec).

RESULTS
Table 1 shows the input required for each problem. The input for each variable is obtained from the statement of the problem given above. The name of the chemical, atmospheric stability, inversion height, wind speed, wind direction, ambient air temperature, and source strength are required for the first five problems. In the sixth problem, values for puddle area and exit velocity are also needed for the computation of the source strength term. If the puddle area is known, it can be used in place of the mass of the chemical spilled, but this assumption might give different results. Since, in an accidental spill, it is relatively easier to estimate puddle area than mass spilled, the area covered by the spilled chemical has been used in this problem. Moreover, the average ground roughness around the spill site must be specified for each problem; the model gives five options.

Table 2 shows the solutions obtained for each of the six illustrative problems. IDLH distances and TLV distances are given in this table along with the arrival times of plume at those distances. The distances give the student an understanding of the potential area of the evacuation zone, and the arrival time helps him/her to appreciate the importance of time available for control measures and evacuation schedules. The TLV distances are higher than IDLH distances because TLV concentration is smaller than IDLH concentration. For Problem 5, the TLV distance is more than 140 times the IDLH distance. In such cases, it may be appropriate to use one-tenth of the IDLH concentration to compute the hazard zone.

The students are asked to change the values of variables in order to understand the importance of the role played by the input data. The graphical display of results is of immeasurable value in accident situations. Three possible plots are included in this paper. Figure 1 is the TLV plot that is obtained from Problem 1, while Figure 2 is the IDLH plot obtained from Problem 2. A plot of IDLH distances for varying in-

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>2.3</td>
<td>140.4</td>
<td>23.5</td>
<td>509.9</td>
<td>1.1</td>
</tr>
<tr>
<td>22.0</td>
<td>17.4</td>
<td>104.6</td>
<td>87.5</td>
<td>2110.8</td>
<td>13.6</td>
</tr>
<tr>
<td>0.2</td>
<td>0.7</td>
<td>0.9</td>
<td>3.0</td>
<td>3.6</td>
<td>0.2</td>
</tr>
<tr>
<td>3.7</td>
<td>5.3</td>
<td>66.4</td>
<td>11.2</td>
<td>14.9</td>
<td>2.1</td>
</tr>
</tbody>
</table>
puts of wind speed for Problem 1 is shown in Figure 3.

CONCLUSION

The CAMEO system is a useful tool for teaching basic concepts related to dispersion modeling of chemical spills. The students are able to conduct computer experiments to enhance their understanding of the effects of accidents involving hazardous chemicals. With increasing public concern of chemical releases and the recent passage by Congress of spill planning regulations (Title III of SARA), inclusion of chemical spill modeling in the chemical engineering curriculum becomes very important. Modeling of spills at fixed base facilities (in advance of a spill) to produce predictions of danger zones is becoming common, and chemical engineering students should be familiar with the modeling methods and public concern of possible dangers of chemical spills.

REFERENCES

12. Nitric Acid: Environmental and Technical Information for Problem Spills, Environmental Protection Service, Ottawa, Ontario, April (1985)
BIOSEPARATIONS: Downstream Processing for Biotechnology
by Paul A. Better, E. L. Cussler, Wei-Shou Hu

Reviewed by
Murray Moo-Young
University of Waterloo

In the broad field of biotechnology, any new book with the words "bioseparations" and "downstream processing" in its title will attract much attention since these are the current trendy, fashionable areas of biotechnology. Somewhat surprisingly, this is probably the first book devoted entirely to this area, which is partly due to the difficulty in handling it for a multidisciplinary audience indigenous to biotechnology. Whereas Volume II of the multi-volume work, Comprehensive Biotechnology (Pergamon Press) is a major reference, this book is a primer on the subject matter. As such, it is a good teaching text and is well worth its list price of $39.95.

The authors, comprising a group of experts with both industrial and academic experience, have developed an effective pedagogical strategy in which typical bioseparations are viewed as an idealized four-step process according to a so-called RIPP organization: Removal of insolubles, Isolation of product, Purification and Polishing. The book helps to bridge the gap between the usually separate, parallel evolving cultures of the life sciences and engineering in this area by providing material for "scientists with no background in engineering" and "engineers with no background in biology." Inevitably, this ambitious approach to satisfy such a wide audience results in sections (e.g., filtration, drying) which are rather rudimentary for chemical engineering graduates (which is the usual level at which biotechnology is taught in chemical engineering departments), while the same sections are too advanced for the life science undergraduates. Regardless, the authors are to be commended for providing in one place "an introduction to the separation and purification of biochemicals."

After an overview introductory chapter, the book is divided into four parts which cover a total of twelve chapters, and ends with two appendices. It is of interest to note the section titles and number of pages allocated to these topics: Overview (11), Filtration and Ultrafiltration (35), Centrifugation (21), Cell Disruption (21), Extraction (47), Adsorption (37), Elution Chromatography (39), Precipitation (17), Ultrafiltration and Electrophoresis (35), Crystallization (35), Drying (29), Auxiliary Operations (12), Characteristics of Biological Materials (5), and Limits of the Continuum Approximations (5). Possibly, a disproportionate amount of space is given to the classical methods of liquid extraction (which is primarily for relatively small molecules in "new" biotechnology terms) at the expense of other aspects (e.g., isoelectric focusing) and recent innovations.

For example, it could be argued that there are a number of other topics or subtopics that should have been covered in a book of this type. Among these are the following: supercritical fluid extraction (its use is increasing); relevant process control and CAD/CAM; multi-unit integration strategies; bioreactor/downstream processing interfacing optimization, bioseparations in microgravity environments (prospects of biomanufacturing on a future space platform are of practical interest); development of new polymeric and composite materials for membrane separations and chromatography column packings; effect of surfactants on membrane separation performance; equipment innovations such as the use of Taylor vortices to reduce polarization effects in membrane separations; the implications of solid-state fermentations to downstream processing economics; materials of construction of the various bioseparation devices. Presumably, the authors could excuse these omissions on the basis of their philosophy that "mixing, like life, is incomplete...!"

The subject matter is given quantitative testament as a series of unit operations (typical of chemical engineering) in terms of mass and energy balance and kinetics of the processes involved. Fundamental concepts are presented clearly. Where correlations derivable from first principles are not possible, the authors draw attention to the traditional usefulness of dimensional analysis for complex flow systems, e.g., the analysis and design of cell disruption devices (Chapter 4). Each chapter contains several illustrative examples and at the end, practice problems with answers (which should please students and practitioners alike) are given. Curiously, some of the problem statements are given in mixed S.I. and British units (e.g., kg, ft) and probably reflects the immediate real-world industry situations addressed. Line diagrams, some with three-dimensional cut-away views, are used to depict clearly the mechanical features and physical functions of various equipment. As a teaching tool, this technique is more effective than photographs.

As suggested by the authors, the book appears to be suitable as a one-semester course for senior undergraduate chemical engineering students and first-year science graduates (including those from chemistry, microbiology, food science). The book should also be useful in industry where calculations in downstream processing are required in research, development, design, and plant operations. The book is sufficiently robust to withstand many hours of use. It has a good subject index, but unfortunately no author index. More discriminating students (and others) would have welcomed some references to the research literature, especially in view of the advances being made in this area. However, this is a minor criticism. Despite the omissions mentioned earlier, the book has something in it for almost everyone interested in bioseparations, a term synonymously now used with downstream processing in biotechnology.
A program on . . .

HAZARDOUS WASTE MANAGEMENT

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Detroit, MI 48202

The need for environmental professionals is escalating. The 1987 Bureau of Health Professionals report, "Evaluating the Environmental Health Work Force," [1] identified 50,000 environmental professionals in the U.S. and projected that by 1992 there will be a need for 100,000. Paul Busch, immediate past president of the American Academy of Environmental Engineers [2], estimates that 22,500 environmental engineers will be needed from 1990 to 1995 "just to meet the problem of hazardous waste clean up." Each year, less than 10% of the hazardous waste engineers that are needed are graduating from our universities [3]. Summit VI, a top level interaction between industry and AIChE (as reported by Mathis [4]), identified the environment and ecology as the number-one growth area for chemical engineers and suggested curriculum changes and more intense training to meet the growing need. Some educational programs have begun to emerge, but not in chemical engineering [5, 6].

The chemical and manufacturing industries are working vigorously to maximize recycle and to minimize waste. Major corporations are establishing their own landfill standards, with their own cradle-to-grave accounting systems and certification of both professionals and facilities. Consulting companies which perform the same services for small industries are thriving.

A new breed of professional, a "chemical control engineer," is emerging. This individual must be technically educated and trained in regulations, but with the focus on management rather than on science or design, and he or she must have such skills as:

- Risk assessment capability
- Computer experience
- Ability to maintain community involvement
- Material use control procedures
- Chemical management systems
- Land use planning
- Knowledge of health issues
- Transportation awareness
- Liability awareness

The boards of major corporations must be informed about these issues on a regular basis. Career path professionals in hazardous waste management will therefore have high rank and pay [7].

Chemical engineers are uniquely qualified to train for this opportunity. A solid background in mathematics, chemistry, and physics, with economics, process control, separations, and a thorough training in logical
thinking and organization, is characteristic of the chemical engineering BS degree. Waste minimization in the chemical industry involves optimization of unit operations, the classic tool of the chemical engineer.

However, within the confines of an ABET-accredited chemical engineering degree, it is not easy to provide the additional education necessary to allow the BS chemical engineer to become a "Chemical Control Engineer." Thus, at Wayne State University we have created a new concept in graduate education, called the "Graduate Certificate in Hazardous Waste Management," which is designed to provide auxiliary education not only to chemical engineers, but also to all conventional science and engineering majors who have the prerequisite mathematics and chemistry background.

This program is a major departure for the chemical engineering faculty. As discussed below, the courses attract a substantial number of non-chemical engineers and as a result constitute the largest service teaching that we have ever undertaken. The chemical engineering profession is uniquely qualified to lead this new effort, but expansion of the traditional tools of chemical engineering will be necessary.

In order to determine the content of the Graduate Certificate program, an interdisciplinary team consisting of faculty and an industrial advisory committee was assembled. A brief description of their backgrounds is given in Table 1.

The program's courses are available as electives to both undergraduate and graduate students in our regular university degree programs, and they have attracted many new students into full-time and part-time programs.

### TABLE 1
Hazardous Waste Management Graduate Certificate Program Participants

<table>
<thead>
<tr>
<th>Industrial Advisory Committee</th>
<th>Faculty</th>
<th>Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>James Carlson, Director, Hazardous Waste Management, Chrysler Corporation</td>
<td>Ralph Kummer, PhD</td>
<td>CHE 751, 726</td>
</tr>
<tr>
<td>Del Rector, Deputy Director, Michigan Department of Natural Resources</td>
<td>James Dragun, PhD</td>
<td>GEL 515</td>
</tr>
<tr>
<td>Myron Black, Director, Environmental Affairs, Dundee Cement</td>
<td>Tim Lang, PhD</td>
<td>CHE 551, 554</td>
</tr>
<tr>
<td>James Dragun, PhD</td>
<td>Carol Miller, PhD</td>
<td>CHE 558</td>
</tr>
<tr>
<td>J. Cho, PhD (deceased, April 1989)</td>
<td>Jeffrey Howard, PhD</td>
<td>GEL 515</td>
</tr>
<tr>
<td>Rick Powalski, Vice President, Petrochem Inc.</td>
<td>Joe Oravac, BS</td>
<td>CHE 554, 556</td>
</tr>
<tr>
<td>Robert Powitz, PhD</td>
<td>Robert Powitz, PhD</td>
<td>CHE 551, 557</td>
</tr>
<tr>
<td>James McMicking, PhD</td>
<td>James McMicking, PhD</td>
<td>CHE 553, 751</td>
</tr>
<tr>
<td>Daniel Crowl, PhD</td>
<td>Daniel Crowl, PhD</td>
<td>CHE 657</td>
</tr>
<tr>
<td>Khalil Alasal, PhD</td>
<td>Khalil Alasal, PhD</td>
<td>CHE 559</td>
</tr>
<tr>
<td>A. L. Reeves, PhD</td>
<td>A. L. Reeves, PhD</td>
<td>OEH 832, 632</td>
</tr>
<tr>
<td>Devon Schwalm, MS</td>
<td>Devon Schwalm, MS</td>
<td>CHE 726, 727</td>
</tr>
</tbody>
</table>

The need for training in hazardous waste control technology, laws, policy, and regulations clearly implies more than the minimum coursework in any single
traditional discipline. Hence, WSU chose to recognize a group of credits as a "Certificate Program," where "certificate" simply refers to university-level recognition and is totally separate from the externally-administered examinations.

Our program consists of a minimum of thirteen credits, distributed as follows:

**REQUIRED**

- **CHE 551. Introduction to Industrial Waste Management** (2 cr: no credit toward a graduate engineering degree)
  The first required course in the sequence is an overview of the program, including topics on solid waste management, site selection, thermal processing, biological waste disposal, hazardous chemical spill clean-up, and hazardous chemical transportation.

- **CHE 554. Law and Administration Issues in Industrial Waste Management** (2 cr: no credit toward a graduate engineering degree)
  The second required course covers management guidelines, Superfund issues, the Solid Waste Disposal Act, identification concepts, standards, reports, permits, and rules.

- **CHE 556. Transportation and Emergency Spill Response** (3 cr)
  This course covers marine, rail and tank truck transport methodology, planning and regulations, and emergency spill response, with field experience.

- **CHE 751. Public Issues of Hazardous Waste** (2 cr)
  This course is devoted to current issues in hazardous waste management and is presented by nationally recognized leaders in industry.

Students will also be required to take an additional four credits from among the following courses.

- **GEL 515. Soils and Soil Pollution** (3 cr)
  The properties and classification of soils are covered. Knowledge of soil properties is used to understand the removal of pollutants from soils and groundwater.

- **CHE 553. Thermal Processing of Hazardous Waste** (2 cr)
  This course covers thermal processing technology, including combustion fundamentals, incineration equipment, waste heat boilers, air pollution control equipment, and facilities design.

- **CHE/CE 558. Land and Ocean Disposal of Hazardous Waste** (2 cr)
  This course covers industrial landfills, biological processes, land disposal techniques, ocean disposal techniques, and the disposal of ashes.

- **CHE/CE 559. Biological Waste Disposal** (2 cr)
  This course, taught in conjunction with Civil Engineering, considers environmental requirements, activated sludge, anaerobic systems, stabilization ponds, dewatering experiments, and activated carbon systems.

- **CE 619. Ground Water** (4 cr)
  Aquifers, aquitards, saturated and unsaturated flow, sources of contamination, artificial recharge, development of basins, and efficient utilization are discussed.

- **CHE 657. Safety in the Chemical Process Industry** (3 cr)
  This course covers the fundamentals and practical experience necessary for safe operation of a chemical process plant, including case studies conducted under an industrial supervisor.

- **OEH 822. Principles of Toxicology** (4 cr)
  Qualified students (those with a biological background) gain exposure to toxicity of industrial chemicals, absorption of gases and dust, laboratory studies of toxicity, inhalation data, and experimentation methodology.

- **CHE 726. Waste Management Internship** (1-3 cr)
  Students earn credit by working in WSU's Environmental Health and Safety hazardous waste program, or other environmental control programs in local industry.

- **CHE 727. Hazardous Waste Laboratory** (2 cr)
  This is a structured laboratory experience in waste characterization, analysis, disposal techniques, and waste minimization.

A "B" average in these 13 credits is required for recognition by the university. Individual courses may
be taken as elective credit toward undergraduate or graduate degrees as well as by non-matriculated students.

An industrial/governmental advisory committee has been recruited, with representation from the basic chemical and automotive industries, hazardous waste operators, consultants, and regulatory agencies. This committee evaluates the program at yearly intervals and suggests revisions in course content for compatibility with current regulations and state-of-the-art technologies.

CURRENT STATUS

The Graduate Certificate program was initiated in the fall of 1986 with the offering of “Introduction to Industrial Waste Management.” There was no formal survey of the students at that time; however, records indicate that the class was composed mainly of undergraduate chemical engineering students. Since the course was given during the day and was not heavily publicized, this was expected. In winter 1987, “Law and Administration in Industrial Waste Management,” “Land and Ocean Disposal of Hazardous Waste,” “Public Issues of Hazardous Waste,” “Waste Management Internship,” and “Hazardous Waste Laboratory” were added to the curriculum. Beginning with that semester, classes were offered in the evening and were publicized to attract graduate and postdegree students. “Transportation and Emergency Spill Response,” “Thermal Processing of Hazardous Waste,” and “Biological Waste Disposal” were added in subsequent semesters.

In the fall of 1988 there were approximately ninety new students in the program, including students in both the regular graduate and undergraduate programs and those enrolled in the Hazardous Waste Management Graduate Certificate program. An offcampus program began in winter 1989 with fifty students. From a modest beginning of 8-10 students per year prior to the introduction of the Graduate Certificate Program, the class has now grown to 140 students per year.

STUDENT PROFILE

For future use in planning, a survey was taken of the winter and fall, 1987, and fall 1988 classes to determine the background and the goals of the students in this program. The total number of students surveyed was 223. Figure 1 shows the baccalaureate degrees of the students in the categories of civil engineering, chemical engineering, geology, chemistry, biology, and other (health management, other engineering, law, business, and liberal arts).

Figure 2 shows the goals of the participants in three basic categories: Graduate Certificate conferred by the University, Certification and Examination by an external agency, and Selected Courses. It should be noted that several participants selected more than one category.

Figure 3 indicates the general areas in which the participants are classified relative to their work or study situation: Hazardous Waste Generators, Hazardous Waste Haulers and Disposers, Environmental Regulators, Students, and Consultants.

![FIGURE 3. Job classification of participants](image)

![FIGURE 4. Academic goals of 1988 participants](image)
TABLE 2
Curriculum: Master of Science in Hazardous Waste Management
Prerequisite/Corequisite: Graduate Certificate in Hazardous Waste Management

<table>
<thead>
<tr>
<th>REQUIRED COURSES</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction to Industrial Waste Management</td>
<td>2 (S/U)</td>
</tr>
<tr>
<td>Thermal Processing of Hazardous Waste</td>
<td>2</td>
</tr>
<tr>
<td>Law and Administration in Industrial Waste Management</td>
<td>2 (S/U)</td>
</tr>
<tr>
<td>Transportation and Emergency Spill Response</td>
<td>3</td>
</tr>
<tr>
<td>Land Disposal</td>
<td>2</td>
</tr>
<tr>
<td>Biological Treatment of Hazardous Waste</td>
<td>2</td>
</tr>
<tr>
<td>Public Issues of Hazardous Waste</td>
<td>2</td>
</tr>
<tr>
<td>Hydrogeology</td>
<td>4</td>
</tr>
<tr>
<td>Waste Minimization</td>
<td>2</td>
</tr>
<tr>
<td>Safety in the Chemical Process Industry</td>
<td>3</td>
</tr>
<tr>
<td>Waste Management Internship</td>
<td>2</td>
</tr>
<tr>
<td>Hazardous Waste Laboratory</td>
<td>2</td>
</tr>
<tr>
<td>Air Sampling and Analysis</td>
<td>3</td>
</tr>
<tr>
<td>Principles of Industrial Toxicology</td>
<td>4</td>
</tr>
<tr>
<td>Design of Chemical Process Experiments I</td>
<td>3</td>
</tr>
<tr>
<td>Probability Models and Data Analysis</td>
<td>4</td>
</tr>
</tbody>
</table>

Minimum Required
(excess credit may be applied to electives)

<table>
<thead>
<tr>
<th>ELECTIVES:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Operation: Unit Processes in Environmental Engg.</td>
<td>4</td>
</tr>
</tbody>
</table>

TOTAL CREDITS
34
(38 including noncredit courses)

MASTERS PROGRAM

Student demand for more information led the faculty and the industrial advisory committee to develop a curriculum for a Master of Science in Hazardous Waste Management. Approximately 37% of the entering class of '88 expressed interest in the full MS program, as illustrated in Figure 4.

The Graduate Certificate is a prerequisite to admission in the Masters program, and all credits are directly applicable toward the Masters. The approved curriculum is listed in Table 2. A full discussion of all the MS courses is beyond the scope of this paper, but graduates will have solid backgrounds in biological and thermal processing, land disposal, hydrogeology, toxicology, laboratory techniques, waste minimization, and chemical process safety.

CONCLUSIONS

It has become evident that industry must learn to design and operate plants to prevent spills and episodes, and to manage their chemical wastes properly. However, it is equally true that they must learn to cope with emergencies and to be able to deal with the public and regulatory agencies before, during, and after such problems.

A graduate certificate program such as the one offered by WSU provides a new avenue of education in this field. The uniqueness of this program lies in the fact that it is area-specific, flexible, and subject to frequent content review. Some changes have already been made, and others are currently under study by the faculty involved in the program, such as the development of the full Masters Degree.

REFERENCES

5. The Environmental Manager's Compliance Advisor, V. 232, 6, June 6 (1988)
PARTICULATE PROCESSES  
Continued from page 215.

ing the relative sensitivity of secondary nucleation to growth rate \( G \) (used as a surrogate variable for supersaturation) and slurry density \( M_T \).

CSD SIMULATION AND MANIPULATION

Figure 1 shows the configuration and theoretical population density plot for both the MSMPR and Double Draw-Off (DDO) crystallizers [6]. The DDO configuration merely removes and then combines two separate slurry streams, one mixed and one classified to contain only crystals less than some cut size \( L_F \). Classification is usually done passively by settling within the vessel. Figure 2 shows the dramatic average particle size increase that this simple configuration can achieve vis-a-vis the MSMPR configuration. Simple power-law nucleation kinetics of the form

\[
B^n = k_N G^i M_T^j
\]

were used for these calculations. As the slurry density also increases in DDO operation this configuration is only fully useful for weak feeds giving a low natural slurry density. Per-pass yield is also increased. Thus, the DDO configuration is also used to increase yield in systems with slow growth kinetics.

Bench-scale studies are currently being done to evaluate the DDO crystallizer as a method of making larger calcium sulfite and sulfate (gypsum) particles in Flue Gas Desulfurization (FGD) processes. Larger particles would greatly reduce downstream costs in such FGD processes.

In ChE-514, students have access to a computer program (Program Crystal Ball [7]) which solves simultaneous population and mass balances for the CSD using arbitrary crystallization kinetics. Students use this program to design a crystallizer producing a desired crystal size and yield.

In summary, the course explores the PSD of particulate processes, while emphasizing the distributed nature of these processes. It attempts to show prediction as well as description of the PSD with the ultimate aim of manipulation. However, these goals are only achieved in the study of CSD from well-defined crystallization processes.

REFERENCES

A course in...

FLUID MECHANICS OF SUSPENSIONS

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SUSPENSIONS consisting of small particles, droplets, or cells dispersed in a liquid or gas are found in a wide variety of natural and industrial processes. We are all familiar with many examples of aerosol suspensions, for which the continuous phase is air (such as smoke, smog, mist, fog, clouds, and various sprays and dusts). We are also familiar with many examples of hydrosol suspensions, for which the continuous phase is water. These include coal slurries, drilling muds, blood, unstrained fruit juice, silt and clay in estuaries, and submerged cultures of microbial, plant, animal, or insect cells. Further important examples of suspensions are paints, ointments, immiscible bimetallic melts, and oil-water emulsions.

A chart showing typical sizes for several types of suspended particles is given in Figure 1. In general, suspended particles are smaller than approximately 100 µm (1 µm = 10^-5 m) in size, since larger particles rapidly settle out of suspension due to gravity. The Reynolds number for flow around suspended particles is typically small compared to unity, and so inertia effects may be neglected relative to viscous forces. Particles smaller than approximately one micron in size are called colloidal particles. They settle out of suspension only very slowly due to gravity. Moreover, because of their large surface area to volume ratio, these particles are subject to Brownian motion and attractive and repulsive interparticle forces.

The behavior of suspensions of colloidal and fine particles represents a fascinating and challenging area for research. There are many active groups studying the fluid mechanics and physical chemistry of suspensions. This research effort needs to be supported by graduate courses which provide students with a fundamental background and the necessary skills for further study of suspensions. In this paper, I summarize such a course that was introduced at the University of Colorado during this past year.

COURSE PHILOSOPHY AND STRUCTURE

The course philosophy is based on two goals:

- To provide the students with a fundamental background that encompasses various aspects of the fluid mechanics and physical chemistry of suspensions.
- To provide the students with an understanding and appreci-
Accordingly, the course is divided into two parts, as outlined in Table 1. The first part consists of lectures which cover the fundamentals of suspensions, and the second part consists of seminars on research frontiers and applications involving suspensions.

TABLE 1
Course Outline

Introduction
- General Features of Suspensions
- Applications Involving Suspensions

Part 1: Fundamentals
- Review of the Equations of Motion
- Creeping Flow Equations and General Considerations
- Motion of a Single Rigid Sphere in a Fluid
- Motion of a Single Spherical Drop in a Fluid
- Motion of Two Interacting Spheres in a Fluid
- Brownian Motion and Diffusion of Suspended Particles
- Interparticle Attractive and Repulsive Forces
- Dimensional Analysis and Order-of-Magnitude Estimates

Part 2: Applications and Research Frontiers
- Sedimentation and Centrifugation
- Coagulation and Flocculation
- Particle Capture and Adhesion
- Microfiltration
- Suspension Rheology
- Drop and Bubble Deformation, Breakup, and Coalescence
- Marangoni Migration of Drops
- Dynamic Simulations of Suspensions
- Fluidization
- Particle Size Measurement
- Particle Size Classification

Accordingly, the course is divided into two parts, as outlined in Table 1. The first part consists of lectures which cover the fundamentals of suspensions, and the second part consists of seminars on research frontiers and applications involving suspensions. These seminars are presented by students who are taking the course, other, more advanced students, guest speakers, and myself. It is assumed that the students have previously taken a graduate level course in fluid mechanics and an undergraduate course in physical chemistry, and that they have a working knowledge of differential, integral, and vector calculus.

FUNDAMENTALS

After an introductory lecture, one lecture period (75 minutes) is spent on a whirlwind review of continuum mechanics for fluids, culminating with the Navier-Stokes equations. The next three lectures focus on general features of the creeping flow or Stokes equations, which result when the Reynolds number is sufficiently small so that the inertia terms (both the local and convective acceleration) may be neglected. One important feature of these equations is their linearity, which allows us to draw many significant conclusions without having to solve the equations. For example, it is easily shown from the reversibility property of linear equations that a non-Brownian particle with fore-and-aft symmetry will not experience a lift force when placed at an arbitrary location in a tube with laminar flow. In contrast, such a particle will experience a lift force and migrate across streamlines when the particle Reynolds number is not small compared to unity. Other features of creeping flow that are covered include general solutions based on harmonic functions and corresponding particular solutions, the fundamental solution for the velocity and pressure fields generated by a point force, the reciprocal theorem, and the boundary integral representation of the Stokes equations. The latter is particularly convenient for numerical solutions of multiphase flow and moving boundary problems, because the velocity field is given in terms of integrals over the boundaries of the domain.

The sixth lecture describes the details of creeping flow past a rigid sphere. The quantity of primary interest, the drag force, is easily found by using the boundary integral equations and the principles of linearity. The complete velocity field in the fluid surrounding the particle is found either from evaluating the integrals that appear in the boundary integral equations, or by using the boundary conditions to evaluate the constants that appear in the general solution to the corresponding differential equations. The following two lectures extend these concepts to the flow internal and external to a viscous drop in creeping motion. Fundamental concepts such as interfacial tension and normal and tangential stress balances are also covered.

Lectures nine and ten describe the interaction of two spherical particles in creeping flow, such as is important for theoretical descriptions of sedimentation, coagulation, and suspension rheology. As a consequence of the linearity of the Stokes equations, this interaction may be decomposed into a superposition of motion along the line-of-centers and motion normal to the line-of-centers. The two-sphere resistance and mobility functions are described, where the resistance functions yield the force and torque on each sphere when their translational and rotational velocities are
known, and the mobility functions yield the translational and rotational velocities when the force and torque applied to each sphere are specified. Asymptotic solutions for these functions are presented using the method of reflections when the spheres are far apart, and using lubrication theory when the spheres are nearly touching.

Shortly after the invention of the optical microscope, scientists observed that very small particles such as bacteria maintained a constant state of random motion when dispersed in water. This phenomenon occurs due to the thermal motion of the molecules comprising the surrounding fluid and is called Brownian motion, after Robert Brown, a Scottish botanist who published his observations in the early 1800s. The classical thermodynamic analysis to yield the Stokes-Einstein diffusivity of Brownian particles is presented in one lecture, and then is supplemented by a second lecture covering the more rigorous derivation based on the Langevin equation for particle motion. Further aspects which are considered include the relative diffusion of two interacting spheres and the spreading of a sedimenting interface due to Brownian diffusion.

The next three lectures are devoted to the interparticle attractive and repulsive forces which arise in colloidal suspensions. It is the relative magnitude of the attractive and repulsive forces which determines whether a suspension is stable (the particles do not aggregate) or unstable (the particles aggregate together in clumps). The attractive forces considered are London-van der Waals dispersion forces, which arise from induced-dipole interactions between the molecules in the two interacting particles. We start with an analysis of induced-dipole interactions between two isolated molecules, and then follow the pair-wise additivity theory of Hamaker (1937) and others to develop expressions for van der Waals attractive forces between macroscopic bodies. Since this approach does not correctly account for screening due to intervening molecules, and retardation due to phase shifts, the more complete continuum theory of Lifshitz and others (see Russel et al., 1989) is also discussed.

The repulsive forces which are considered are primarily electrostatic due to charges on the particle surfaces, although Born repulsion and steric and charge stabilization due to adsorbed polymers are also briefly described. When the charged particles are present in a solvent containing ions, a double-layer with an excess of counter ions will form around each particle, thereby reducing the repulsive force between two particles of like charge. The potential field in the ionic solution is described by the Poisson-Boltzmann equation. The analytical and numerical solutions to this equation and its boundary conditions are presented for a variety of cases. The solutions lead to expressions for the electrostatic repulsive force between charged objects. Finally, these are combined with the expressions for London-van der Waals attraction to yield the DLVO theory for the net force potential as a function of the separation distance between two particles.

The final lecture of Part 1 of the course is a review which is accomplished by collecting the expressions which have been derived for the various forces acting on colloidal and fine particles in suspensions. These include gravity, viscous, inertial, Brownian, van der Waals, and double-layer forces. Order-of-magnitude estimates for these forces as functions of particle size and separation are made. By comparing the relative magnitudes of the forces, it is easy to see which forces typically dominate for different size ranges and particle separation distances. This analysis leads naturally to the identification of key dimensionless groups, such as the Reynolds number (ratio of inertia to viscous forces) and the Peclet number (ratio of convection to diffusion).

RESEARCH FRONTIERS AND APPLICATIONS

I start off the second part of the course by giving one overview lecture which briefly describes selected
practical applications and current research activities involving suspensions. The ones chosen for this past year are listed in Table 1. Most of these were then elaborated on in a seminar-style format by myself, a student, or a guest speaker. Brief summaries are given in the following paragraphs.

Sedimentation and centrifugation are commonly used to separate particles from fluid; they also form the basis for indirect measurements of particle size. A few areas of current research interest include hindered settling and hydrodynamic diffusion due to particle interactions, enhanced sedimentation in inclined channels, lateral segregation and instabilities in sedimentation of bidisperse (two particle sizes or types) suspensions, and analysis of flow patterns in centrifuges. One of our seminars this past year covered recent advances in sedimentation in inclined channels (Figure 2), and another described the spreading of the interface at the top of a sedimenting suspension due to the collective action of hydrodynamic diffusion, size polydispersity, and hindered settling.

In order for particles in a suspension to coagulate, aggregate, or flocculate, the particles must first be brought close together by Brownian motion, differential sedimentation, or stirring. They then must experience an attractive force which is sufficiently strong to overcome any repulsive force and the fluid-mechanical lubrication resistance to relative motion. Considerable recent research on Brownian-induced, shear-induced, and gravity-induced flocculation has extended the early collision models of Smoluchowski (1917) to include the effects of hydrodynamic interactions and interparticle attractive and repulsive interactions. One of our seminars described a model for predicting the rate of doublet formation in a polydisperse suspension due to the combined action of gravity sedimentation and attractive van der Waals forces. Further current research on flocculation involves the experimental and theoretical elucidation of the loosely-branched fractal structure of aggregates of colloidal particles or microbial cells (Figure 3).

Two different types of filtration to remove small particles from gas or liquid streams are common. Particle capture and adhesion are the underlying processes in deep-bed filtration by stationary collectors such as granular beds and fibrous mats. The basic concept is that a gas or liquid stream is passed through the filter, and the suspended particles collide with the collecting elements due to their inertia or Brownian motion and adhere to them as a result of attractive forces. Current fundamental research on particle capture and adhesion was reviewed in one of the seminars and includes determining fluid flow patterns and particle trajectories in deep-bed filters, predicting the conditions for which the colliding particles will adhere as opposed to bounce, and examining the influence of particle inertia, Brownian motion, interparticle attractive and repulsive forces, and hydrodynamic interactions on capture rates.

The second type of filtration considered is crossflow microfiltration, in which a suspension under pressure is passed through a narrow tube or channel having microporous membrane walls (Figure 4). The solvent and small molecules pass through the walls as permeate, whereas the particles are retained on the membrane surface. If these particles are allowed to accumulate in a stagnant cake or fouling layer adjacent to the membrane, then the permeate flux rate is

![FIGURE 3. Aggregates of yeast cells with loosely-branched fractal structure.](image)

![FIGURE 4. Schematic of crossflow microfiltration.](image)
reduced. In order to understand and overcome this phenomenon, current research is directed at describing how the shear stress exerted at the membrane wall by the tangential flow of suspension through the filter tube or channel is able to limit the buildup of a fouling layer.

Suspension rheology refers to the flow behavior of suspensions. Suspensions often exhibit non-Newtonian rheological behavior, in large part due to interparticle attractive and repulsive forces and Brownian motion. In addition to studies of non-Newtonian behavior, considerable theoretical and experimental research is currently directed at extending Einstein’s relationship for the effective viscosity of a sheared suspension. Another active research area involves shear-induced hydrodynamic diffusion, for which particles migrate across bulk streamlines due to hydrodynamic interactions with other particles. The key role that this phenomenon plays in crossflow microfiltration was described in one of the seminars.

Drop and bubble deformation, breakup, and coalescence play key roles in a variety of important processes, such as raindrop growth, liquid-liquid extraction, mixing, dissolved oxygen transfer in fermentors, and materials processing of bimetallic melts with a liquid-phase miscibility gap. Accordingly, research in this area is very active. Boundary integral methods are used to study the deformation and burst of single drops, as well as the motion and deformation of two interacting drops. Lubrication forces, van der Waals interactions, and interfacial phenomenon have been shown to significantly affect film drainage and film rupture between two colliding drops or bubbles. One of our seminars this past year reviewed techniques such as bispherical coordinate transformations, multipole expansions, and lubrication theory coupled with boundary integral methods for describing the hydrodynamic interaction between two spherical drops in creeping flow. Two other seminars dealt with population dynamics models and holographic techniques for predicting and measuring, respectively, shifts in drop size distributions due to collisions and coalescence.

When a drop (or bubble) is placed in an otherwise quiescent liquid on which a temperature gradient is imposed, it will migrate (in addition to its motion due to gravity or other external forces) toward the region of higher temperature. This phenomenon is referred to as thermal Marangoni migration or thermocapillary migration and occurs because the interfacial tension decreases with increasing temperature. The interfacial tension difference between the hot and cold sides of the drop sets up a circulatory motion so that the drop, in effect, “swims” up the temperature gradient. This migration was first analyzed by Young et al. (1959) under conditions of small Reynolds and Peclet numbers. Current research was reviewed in one of our seminars and includes extending the analysis to higher Peclet numbers, considering the interaction of two drops or bubbles in a temperature gradient, and analyzing the analogous phenomenon of solutal Marangoni migration of a drop or bubble in a concentration gradient of a surfactant.

Recently, Brady and Bossis (1988) and co-workers have developed a method to dynamically simulate the behavior of many particles suspended in a fluid. The method incorporates hydrodynamic interactions between particles, at least in an approximate sense, as well as other forces applied to particles, such as gravity, Brownian forces, and attractive and repulsive interparticle forces. This method, known as Stokesian dynamics, follows the position and velocity of each of the suspended particles as functions of time, for suspension flows such as sedimentation and simple shear. Although excessive computational requirements generally limit the simulations to a monolayer of suspended particles, they are able to predict macroscopic information, such as effective viscosities or average hindered settling velocities, as well as microscopic information, such as the local arrangement or microstructure of the particles as it evolves with time (including addressing questions such as whether or not the particles tend to cluster).

Another application area for research involving suspensions is that of fluidized beds, which are common in the chemical process industry. Solid particles at rest in a vertical column form a packed bed through which fluid may be forced. If the rate at which fluid is forced through the bed exceeds a critical value (i.e., that for which the drag force exceeds the gravity force on the particles), then the particles are lifted and separated from one another. The bed is then said to be fluidized. If the fluid velocity is increased further, the fluidized bed will become unstable. Bubbles of fluid that are relatively free of particles will form near the base of the bed and rise through it. As a result, partial by-passing of the particles by the fluid occurs. In addition to studies of these instabilities and bubble formation, current research on fluidized beds includes studies of particle attrition and of hindered settling of
particles relative to the fluid.

For a variety of reasons, it is important to know the size distribution of particles in suspension. This is particularly true for the design of solid-liquid separation equipment, particle size classifiers, and catalytic reactors. The many methods available for sizing particles include electrical conductivity, gravitational and centrifugal sedimentation with light extinction, hydrodynamic chromatography, photomicroscopy, optical blockage or shadowing, light scattering, aerosol inertia, diffraction, field-flow fractionation, gas adsorption, elutriation, and holography. Seminars presented by students this past year included light scattering and holographic techniques for measuring particle size distributions.

The final application area considered in Part 2 of the course involves particle classification, where classification involves the separation of particles according to size, shape, or density. A variety of commercial devices are available for particle classification. These include screens, elutriators, continuous centrifuges, and cyclones. A single pass through one of these devices will divide a feed stream into a coarse fraction and a fine fraction. One of our seminars focused on elutriators, which require the particles to settle against an upward flowing liquid stream. Classification occurs due to differences in the sedimentation velocities of the particles. Fundamental analyses to predict the compositions of the product streams are possible for relatively simple geometries, such as a rectangular channel inclined from the vertical.

READING MATERIAL

As is often true of advanced speciality courses, there is no single textbook which covers all of the material presented. A new text which covers most of the fundamental material and some of the application areas is Colloidal Dispersions, by Russel, Saville, and Schowalter (1989). Another new text, which focuses on mathematical treatments of fundamental fluid mechanics of noncolloidal suspensions, is An Introduction to Microhydrodynamics, by Kim, Karrila, and Jeffrey (1989). I thank Bill Russel and Sang Kim for providing me with advance copies of the relevant chapters of these texts. These and other useful books are listed in the reference section. Also provided is an extensive, but by no means exhaustive, list of technical and review articles on suspensions.

Since the lectures cover considerable complex material, I wrote them out in advance in order to provide copies to the students. Similarly, copies of the overheads or text for each seminar are provided to the class. This minimizes the requirement for notetaking and allows the students to participate more fully in the class discussion.

ASSIGNMENTS AND GRADING

Several homework assignments are given in order to provide the students with a deeper understanding of the fundamental material on suspensions presented in the lectures, and to give them practice with the necessary analytical tools. An in-class midterm examination is given at the end of Part 1 of the course, covering the fundamentals of fluid mechanical and colloidal aspects of suspensions. During Part 2 of the course, each student prepares a written paper reviewing the state-of-the-art of a particular research subject that falls under the general theme of the course. These papers are of 10-15 pages in length and are prepared in a journal-style format. Each must review at least two journal references from the past decade. The students also present their review papers to the class in a seminar-style format.

The course is graded with equal weighting on the homework, the midterm, and the review paper. In addition, regular attendance and participation in critical discussions are expected. Since speciality courses are usually small in size (we had eleven students in this course last fall), there is plenty of opportunity for all to participate. An effective way to promote this is to take the class on a mini-retreat early in the term. We went to the Mountain Research Station of the University of Colorado one Saturday last fall, where I delivered three of the lectures interspersed with lunch and volleyball games.

CONCLUDING REMARKS

Suspensions represent a fruitful area for fundamental research with a wide variety of important applications. This course provides graduate students with the fundamental background that is needed to pursue this research. It also provides them with a broad understanding and appreciation of the current applications and research frontiers in this area.

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LETTER TO THE EDITOR

Continued from page 203.

Times of economic crisis cut their own compensation first. (In the last two years, Japanese manufacturers cut their executive salaries to absorb the external shocks of the appreciating yen.)

Many American corporations now are seeking to lessen the damage of management versus labor battles by giving more workers a chance to advise on corporate methods and strategy in the workplace. In the meantime, in the universities, there has been a proliferation of managers, the very well-paid academic and non-academic administrators who don’t teach. So the universities, always about a decade behind the rest of the country, are just now discovering how privileged the management class has become and finding ways of distancing the managers and functionaries from the professors. We see administrative layer upon layer burgeoning, with proportionately less support available to serve those of the academic “production” side. This hierarchy in a university bureaucracy creates alienating conditions deterring communication between the classroom and the laboratory on the one hand and the deans, vice presidents and the president on the other.

A perception of privilege undermines a sense of community on many campuses. University administrators in major universities around the country, for example, drive university cars, with reserved parking places. They may also have free memberships in social clubs. A clear message of power and privilege, symbolically and actually, is communicated to all. The atmosphere and class distinctions become moralizing. Privileges are perceived not as nurturing qualities of commitment to the life of the mind, nor qualities promoting loyalty to the institution. Much of a university’s energy today is invested in perpetuating the non-academic instruments of control and maintaining the structure of a self-perpetuating bureaucracy.

The heart and reputation of a university, and the affection and esteem in which it is held, do not reside solely in the dollars awarded its research professors by extramural agencies. Rather, the perceived greatness of its commitment to the education and nurturing of its students and the respect accorded faculty and their creative works, determine the long-term well-being of the university. Every student graduating from the institution, and all its faculty members, promote the university in terms cynical or laudatory, depending on his or her experiences. Thus the faculty and administrators ought to enhance its institution’s well-being by promoting the self-esteem of the students and faculty. Students and faculty are inexorably linked. This means fostering collegiality, reducing the sense of an impersonal and disinterested bureaucracy. It means finding out, perhaps by exit interviews with graduates, what is actually happening within the university (rather than doing surveys on quality of life). The same ought to be done with departing faculty members. Paying attention to practical problems such as the availability and cost of parking, courtesy, maintaining clean classrooms, and promptness of response to inquiries are ways university administrations can show respect for the needs of students and faculty. It also means the president and vice presidents and deans should meet with faculty members and students at the working academic level, the basic teaching units of the university. Wanting to do these things and more would be a unifying influence. This requires, ultimately, the recognition that all administrators are temporary caretakers for the new generations of students always coming and going and respecting the teachers who transmit their learning and pursue new knowledge. The history and continuity of a university resides in the quality of work and loyalty of its students and faculty and the non-academic workers who serve in making the central purposes of the university easier to accomplish.

Daniel Hershey
Professor of Chemical Engineering
University of Cincinnati
and former Assistant to the President under Warren Bennis
A course on . . .

APPLIED LINEAR ALGEBRA

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In both industry and academics, as the emphasis on multivariable control designs develop, it becomes indispensable that the concept of linear algebra and its geometric and physical interpretations be mastered as background knowledge. As graduate courses introducing recent developments in the theory and design of multivariable process controls emerge in the graduate curriculum, a concomitant background course in applied linear algebra becomes imperative in understanding the new complexity of multivariable control. Three years ago, the chemical engineering department introduced a new course, cross-listed in both the electrical and computer engineering and the mechanical engineering departments, entitled “Application of Numeric Linear Algebra in Systems and Control Engineering.” All chemical engineering graduate students in the system modeling and process control areas and all electrical engineering students taking the graduate linear systems theory course are required to take this course. A prerequisite is senior or graduate standing with a prior introductory undergraduate course to vectors and matrices.

The students usually come into the course knowing only how to do matrix addition, subtraction, and multiplication—finding the determinant and inverse of up to 3x3 matrices. Some of them know a little about basis vectors and have some notions about linear independence of vectors. In all three departments, the students can use this course to satisfy one of their math course requirements. All other graduate students are strongly encouraged to take this course.

The goal of the course is to introduce engineering students, especially those majoring in the systems and control area, to the concepts and the physical as well as the geometric interpretations of some key linear algebra topics and their associated numerical considerations. Examples from system modeling and control areas are used extensively in order to lend a sense of reality to the rather abstract mathematical concepts. In this article, we describe the course teaching philosophy, the computer projects assignments, and the student feedback. We have received such favorable comments and support from the faculty and students that we plan to offer it annually in the fall semester. It will also serve as a corequisite for the 500-level course on linear systems theory offered by the electrical and computer engineering department.

In a previous article [1] published in the fall, 1984, issue of Chemical Engineering Education, entitled “Linear Algebra for Chemical Engineers,” K. Zy- gourakis (Rice University) describes the linear algebra course as the first semester of a two-semester sequence applied math course. Our course at the University of Tennessee differs from that in that we emphasize the geometric and physical interpretations of the various theorems and decompositions in order to develop, in the students, the ability to answer for themselves questions such as, how do I go about computing the controllable or observable subspace of a dynamic system; how do I use the concept of rank and linear independence to analyze a set of input and output data of a given process; how do I use the concept of orthogonality in analyzing a system matrix; how can I tell if a particular algorithm for system analysis is prone to numerical instability; what is the role of positive-definite matrices in an optimization problem; what does it mean for two physical system matrices to be connected by a similarity transformation; what is the danger of a pole-zero cancellation of a transfer function?

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CHEMICAL ENGINEERING EDUCATION
We hope that students will be able to start developing an intuitive understanding of the relationship and interactions among the several system variables by analyzing the matrices that connect between them, thereby guiding them in choosing the most appropriate design and analysis methods. We do not emphasize the writing of computer codes to implement the various numerical algorithms because we recognize that reliable numerical software exists (such as MATLAB [2, 3] that is mainly based on stable routines contained in such packages as LINPACK [4] and EISPACK [5] for various computer models). Rather, we use the software to solve some physical problems or to implement a certain algorithm in order to study the numerical aspects of it. We are trying to impart to the students the intuitive ability to examine a system and by using fundamental linear algebra concepts, to extract physical information from it. For instance, in considering the placement of temperature sensors along a distillation column, how does one decide where to place them in order to extract the most useful information about the behavior of the column from their measurements? Or, in mechanical engineering, where should the accelerometers be placed along a beam in order to detect the first N modes of vibration due to a set of inputs? It can be shown [6] that the choice is the sites where the gain matrix between the control inputs, e.g., reflux ratio, and bottom heat duty, and the system outputs, e.g., the temperature measurements, that yields the smallest condition number and that has the largest sensitivity in the gains, or a compromise of the two, because this arrangement implies a more balanced distribution of energy involved in each of the control input variables.

As the description of a system changes from single variable to multivariable, very often the single-variable concepts, such as size and interaction, do not carry straight forward into the multivariable case. In the latter, the concept of directionality as exhibited by the various variables and their interactions with each other necessitates the use of a set of coordinate systems to describe the dynamics. The motto “happiness is finding things are linear” extends into the realm of linear algebra in that “happiness is finding that coordinates are perpendicular”; therefore, the various decompositions (such as QR, SVD, Householder) emerge so that a system can be transformed into a new representation with mutually orthogonal basis vectors.

True, all these theories and algorithms involved are normally covered in upper-level mathematical courses offered by a math department. One asks, legitimately, why is the engineering department bothering to cover the same materials? Why not just send the graduate students over to the math department? The answer is that unless the math department maintains a constant liaison with the various engineering departments in order to monitor their need in higher level mathematics, the courses they offer will usually not serve the needs of the engineering students who want to use the mathematics as tools in solving practical problems.

Take linear algebra as an example. At the University of Tennessee, three undergraduate courses (semester) exist in the theory and numerical aspects of linear algebra; at least four graduate courses exist that deal with the theory and algorithms of various topics of linear algebra, such as solving the least square problem and the various decompositions. Engineering students who take them come away knowing how to perform a certain decomposition or how to calculate the eigenvalues and eigenvectors, and have learned the numerical aspects of the various algorithms. But they have not acquired the intuition relating knowledge of the mathematics to selection of the methods for analysis, design, and control of physical systems. Study of the properties of linear vector spaces should be linked to the notion that the state space of a dynamical system constitutes a linear vector space and that the controllable and/or observable space constitutes a subspace of the original state space. Then all the manipulations, such as change of basis, orthogonalization, QR, and SVD, can be viewed as a way to view the system states in a more facilitating coordinate frame (orthogonal), and the system matrices or transformation matrices can be viewed with respect to these new coordinate frames. As a result, the properties associated with these special matrices, such as unitarity, orthonormality, and triangularity, can be used to view the transformation as represented by these matrices in a more intuitive and simplified manner. An area where a variety of physical problems can be used to illustrate the math principles is that of using SVD and pseudoinverse in solving least-square problems. In the long run, we hope that the experience gained in teaching both the engineering and mathematical version of the materials can lead to a single course meeting the goals of both groups.

The textbook used is *Linear Algebra and Its Applications* [7], by Gilbert Strang. Table 1 lists the
textbook along with the supplemental reference books, and Table 2 shows the topics covered in the course. From time to time, details of some topics are also presented from references listed [8] and [9]. Strang presents the materials as a systematic development of observations on a set of linear algebraic equations (later on, on a set of linear ordinary differential equations). His presentation elicits enthusiasm from the readers until the mystery of observations is solved, seemingly intuitively. Then, voilà, he formally states the deductions in theorems. He leads one from the beginning to the end of the development of a concept in such a manner that one cannot help following him in order to see the interpretation of the observations! Most students in the class also appreciate Strang’s style of presentation.

Over half of the class time is devoted to the first three chapters, involving analysis of solving the problem of $Ax = b$, the over- and under-determined, and the inconsistent cases. After the mechanism of Gaussian eliminations with pivoting is presented, the concept of the four fundamental subspaces is introduced. Geometric visualization of the orthogonal complementary subspaces, e.g., the row and null spaces, is stressed. The roles of the four subspaces with respect to linear transformations are, in turn, explained and visualized in detail. The decomposition of any vector into its orthogonal components is emphasized. In geometric visualization, a three-dimensional space is always used because of its familiarity. Then, the visualization of the vectors $b$ and $x$, as in $Ax = b$, in the recipient and domain space, respectively, of the linear transformation represented by the matrix $A$, is made. Figures 1 and 2 (from Strang) are used very often to depict the actions of $A$ and the Moore-Penrose pseudo-inverse, $A^+$, with respect to the four subspaces. The role of each of the four fundamental subspaces with respect to the under- or over-determined and inconsistent cases is analyzed in detail. At this point, an example is given concerning the underdetermined case. The problem is presented of a physical process with more inputs than outputs, and they are related at steady state, by $A$, as in $y = Au$. The dimension of $A$ is therefore rectangular, $m \times n$, with $m < n$, more variables than constraints. Therefore, from linear algebra theory, many solutions exist. One can pose an optimization problem where one wants to find the solution, $x_{op}$, from the set of all possible solutions, such that some function of $x_{op}$ is minimized (or maximized).

A physical example where an inconsistent case of $Ax = b$ may arise is offered at this point. Cases involving multiple measurement data points are the most common. A specific example, mentioned earlier, is one of temperature sensor measurements along the many trays of a distillation column. Usually, two control inputs are considered. Yet there may be five or more

<table>
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<th>TABLE 1</th>
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<td><strong>Course Textbook</strong></td>
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<td>• Complex matrices: Symmetric vs. hermitian and orthogonal vs. unitary</td>
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temperature measurements along the tower. The matrix that relates the inputs and outputs would be of dimension 5x2. Because of noise or biases, the temperature measurements would usually be inconsistent when compared to that calculated from the physical and thermodynamic data of the components and process involved. The solution to $A\mathbf{x} = \mathbf{b}$ in this case represents the input necessary to give a set of measurements “closest” to the desired outputs as measured by the sensors. These presentations on the four fundamental subspaces pave the way for introduction of the singular value decomposition (SVD), the pseudoinverse, and application of SVD in solving the least-square problems. SVD has proven to have many applications in system analysis and plays a major role in the implementation of many stable numerical algorithms. See Klema and Laub [10], for example, for more detailed discussion concerning the numerical aspect of SVD.

Let $A = U\Sigma V'$ be the SVD of $A$. We present the notion that transformation of a vector $\mathbf{x}$ by $A$ can be viewed as series of transformations: first a rotation by $V'$, a unitary matrix, followed by a decoupled transformation represented by the diagonal $\Sigma$, followed by another rotation by the unitary $U$. The notion that the columns of the matrices $U$ and $V$ in serving as the orthonormal basis vectors of the appropriate subspaces is presented.

The concept of singular values of a matrix is presented as follows (this geometric representation is borrowed from that of Moore [11]). If an r-dimensional sphere of unit radius resides in the row space of matrix $A$, with the r orthogonal unit vectors given by the first r columns of the matrix $V$ as the coordinate axes ($r$ denotes the rank of $A$), then the transformation process maps it into an r-dimensional ellipsoid in the column space of $A$. The nonzero singular values of $A$ represent the magnitudes of the axes of the ellipsoid (the largest singular value gives the length of the major axis, etc.). The mutually orthogonal axes of the ellipsoid point in the directions given by the first r columns of the matrix $U$. In this way, the singular values can be viewed as scaling factors for the unit radii of a sphere in the row space when mapped into an ellipsoid in the column space of $A$. Again, the students are asked to picture the various manipulations in 3-D space. Finally, the concept of the pseudo-inverse of $A$ is presented. The roles of $U'$ and $V$ in accomplishing projection and change of basis are carefully presented, using Figure 2 as an aid.

At this point, a computer assignment is made for finding the completely controllable, completely observable, and completely controllable and observable subspaces of a linear dynamic system, described by the equation $\dot{\mathbf{x}}(t) = A\mathbf{x} + B\mathbf{u}$, where $\mathbf{x}$ represents the state vector and $\mathbf{u}$ represents the input vector. The idea is that from the controllability and observability grammians of the system, (positive definite solutions, $P$ and $M$, to the Lyapunov equations, below)

$$AP + PA' = -BB'$$
$$A'M + MA = -C'C$$

one can project the original state space down to the controllable or observable subspace spanned by the columns of $P$ or $M$, respectively, by doing an equivalence transformation, using a set of orthogonal basis vectors that span the appropriate subspace, for the transformation. The rank of each of the subspaces is the rank of $P$ or $M$ respectively. Stable routines exist for solving equations of the above type. The matrices $P$ and $M$ can also be solved in a stable manner by assuming a QR decomposition of $A$, and in conjunction with back substitutions, the elements of $P$ and $M$ can be determined in a straightforward manner.
This exercise also illustrates that often a good algorithm can be ruined by bad numerics. Let me explain. The controllability or observability of a system can also be analyzed by examining the rank and the span of the associated controllability or observability matrix U and V as calculated by

\[
U = [B| AB| A^2B| ... | A^{(n-1)}B] \\
V = [C| CA| CA^2| ... | CA^{(n-1)}]
\]

respectively. In order to calculate U and V, repeated multiplications by A up to (n-1) times are necessary. If n is large and A is poorly conditioned, then it can lead to numerical instability such that rank determination of the resultant U and V may be obscured by their near singularity; the singularity may have been an artifact of the numerics and not necessarily a representation of any physical defect. For the completely controllable and observable system, one finds the intersection of the two respective subspaces by projecting, for example, the controllable subspace down to the observable subspace. A good illustration of applying numerical linear algebra to system concept here is that if one only desires to test the controllability (observability) of a system, one can normally get accurate results by applying a random state feedback (observer) through gain K (F), to form A + BK (A + FC) in the state propagation equation, where K (F) is randomly chosen. Then one computes the eigenvalues of A and A + BK (A + FC) and pair off nearest eigenvalues between the two matrices. The system is completely controllable (completely observable) if, and only if, the two matrices A and A + BK (A + FC) have no common eigenvalues with probability 1.

About two thirds of the course is spent in covering the first three chapters and the appendix on pseudoinverse, which we consider to be the heart of the matter. Each notion is presented geometrically and intuitively as much as the subject matter allows. Sometimes it takes quite a few lectures to get an idea across. But each decomposition and manipulation is accompanied by an explanation of why one wants to do that decomposition and manipulation and what does it get you? As many physical examples are offered as possible. In this respect, Strang's presentation of the material does lend a much more intuitive appeal than some of the other textbooks.

SECOND HALF OF COURSE

The second portion of the course starts with a review of the properties of determinants. This is followed by the next four chapters on eigenvalues and eigenvectors, positive definite matrices, computations with matrices, and linear programming. The book is followed fairly closely except for the chapter on computations with matrices. For this subject matter, Strang is supplemented by materials from Stewart [8] and Golub and Van Loan [9], which both deal with the numerical aspect of matrix computations. The Gaussian elimination with pivoting is presented first, and is followed by the Householder's transformation and upper Hessenberg matrices and their significance in speeding up the computation efficiency. The condition number and the Raleigh's quotient of a matrix are discussed with respect to stability and perturbation.

At this point, physical examples are offered to illustrate the danger of dealing with a matrix with a high condition number. The students are asked to visualize a system with states residing in an ellipsoid with two long major axes and a very short third minor axis. Suppose one wants to find the control input required to produce some desired states. Such system matrix with high condition number would yield a very large control input upon inversion of the matrix. Therefore, the students are asked to ponder if it would not have been more appropriate to lop off one dimension (the one spanned by the short axis) and project the original system down to a subspace with dimension of one less.

A computer project is assigned to consider a 2x2 case where the gain matrix of a system is derived experimentally where the measurements are rather noisy. The students are asked to calculate inputs necessary in order to yield certain output vector values. The condition number of the gain matrix given is rather high due to the fact that the real gain matrix is singular, because only one of the two outputs is independent. But, due to noise, the experimentally derived gain matrix is not singular, but rather is near singular. The students are to compare the sensitivity of the calculated results using the original full matrix with slightly varying entries to reflect the noisy nature of the data. Further, they are asked to offer a plausible explanation for the high sensitivity of the calculated results to the slight perturbations in the system matrix entries and to offer a solution for avoiding this problem. The students are asked how to compute, using SVD, the reduced order models to eliminate modes which have little effect on system response. They find this exercise enlightening.

The presentation of eigenvalues and eigenvectors is straightforward. The intuitive approach has not been used much except where the notions from the first part of the course apply. A note has to be said
about the Jordan canonical form of a matrix A. In every linear algebra textbook there is a section devoted to the explanation and calculation of the Jordan canonical form of a matrix A. Some emphasize it more than others. However, when dealing with large systems (as in many practical problems) where computers are employed for matrix manipulations, an approach employing the calculation of the Jordan decomposition, i.e., \( X^{-1} AX = \text{diag}(J_1, \ldots, J_t) \), where each J is a Jordan block, is not numerically stable. This comes about because at several steps of calculating the decomposition, rank decisions must be made, and the final computed block structure depends heavily on these blocks, thus on these rank decisions. In practical applications, Golub and Van Loan suggest using the more stable Schur decomposition in eigenvector problems. Therefore, the Jordan canonical approach is not covered in detail in this course.

The course has now been taught twice at our university, and the students have received it with enthusiasm. Many of them have taken courses in linear algebra in the mathematics department prior to taking this course. They comment that the approach taken here is very different and that their intuitive understanding of the key theorems has increased. They further state that this course has helped them to better understand papers involving matrix manipulations.

CONCLUSION

A new applied linear algebra course, cross-listed in three engineering departments, has been created. The emphasis is on intuitive understanding and geometric visualization and interpretation of the key theorems of linear algebra. The students should learn the why's of doing certain matrix decompositions and manipulations and should be able to visualize the algorithms in 3-D space. Numerous physical examples from systems area are offered, tying together the mathematical manipulations and their physical significance. Computer projects are assigned from time to time to illustrate the utility of the various algorithms in solving practical problems. The course has also been made a co-requisite for the linear systems theory course offered by the electrical engineering department, so as to take the pain of teaching simultaneously both the applied linear algebra and linear systems theory out of that course. The students who have taken the course appreciate its approach, and I have found that every time I have taught it, I find more points that I am able to interpret intuitively that I was not able to before. The Chinese have an old proverb that says that new things are learned from reviewing old things. It has proven to be the case with this course.

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RANDOM THOUGHTS

Continued from page 207

Alternating between the roles of student advocate and guardian of standards—good cop and bad cop—enables teachers to serve comfortably in both capacities. It’s easier to set high standards if you know you’re going to be helping the students attain them, and it’s easier to enforce the standards once you’ve made them quite clear and given the students every opportunity to meet them. In addition, the approach may also provide a significant fringe benefit:

In the end, I do not think I am just talking about how to serve students and serve knowledge or society. I am also talking about developing opposite and complementary sides of our character or personality: the supportive and nurturant side and the tough, demanding side. I submit that we all have instincts and needs of both sorts. The gentlest, softest, and most flexible among us really need a chance to stick up for our latent high standards, and the most hawk-eyed, critical-minded bouncers at the bar of civilization among us really need a chance to use our nurturant and supportive muscles instead of always being adversary.

There’s much more. Get the book.

REFERENCES

INITIATING CROSSDISCIPLINARY RESEARCH
The Neuron-Based Chemical Sensor Project

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Chemical engineering is essential to the process of bringing new areas like biotechnology, electronic, and other advanced materials to commercial success. The success of this process depends on significant cooperation between chemical engineering and other disciplines. Although there is a large volume of literature on the subject of interdisciplinary and/or crossdisciplinary research [1-3], most of it concerns large projects (as defined in Table 1) and little has been written from a chemical engineering perspective. The rationale behind the levels of funding used in Table 1 is called for. Usually in the initial stages of a project, $30,000 to $70,000 for a single year is only sufficient to generate pilot data and perhaps to provide incentive for the formation of a cross- or an interdisciplinary team. A yearly budget of $70,000 to $150,000 for a period of three to five years provides enough for more than one graduate student to focus on specific aspects relating to the expertise of each co-investigator. Amounts above $150,000 can support large groups with more personnel per discipline involved as well as supporting inter-university research activities where extensive travel may be necessary. The purpose of this paper is to address the problems of initiating and conducting a small university level crossdisciplinary project with a yearly budget at $30,000-$70,000. As an example, specific reference is made to a Washington State University (WSU) project on neuron-based chemical sensors which involved chemical and electrical engineers as well as neuroscientists and an immunologist. The experience gained by this group in putting together a research team from various disciplines could be of value to chemical engineering professionals, particularly for young faculty and graduate students who are considering multi-disciplinary projects.

DISCIPLINE AND CROSSDISCIPLINARITY

What is a discipline? Generally the term ‘discipline’ refers to a specialized field of knowledge. Swanson [4] has pointed out that disciplines in a university environment develop when both faculty and administration come to recognize reasonably distinct areas of inquiry. It is important to realize that each discipline is usually composed of a set of narrower specializations and that the comprehensiveness of the discipline has at least three properties [5]: 1) a conceptual model shared by individual members that forms the heart of the discipline—an example is the paradigm of transport phenomena, presented in the 1960 textbook by Bird, Stewart, and Lightfoot, which suggests that the proper study of chemical engineering is the molecular phenomena that are fundamental to the understanding of the performance of chemical equipment; 2) a set of phenomena common to the various specializations (e.g., chemical kinetics, thermodynamics, and others); and 3) breadth of the discipline, achieved through overlapping of multiple narrow specializations of different individuals as opposed to being embodied in one scholar. Through this overlap comes cohesiveness, and a common discipline language, or jargon, develops to an extent less possible between disciplines [4].

It should be mentioned that currently there is no agreement among practitioners of multi-disciplinary research on a unifying terminology. However, there is a need for such a consensus. The interchangeable

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TABLE 1
Project Size Based on Yearly Budget

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<tr>
<th>Project Size</th>
<th>Yearly Budget (US $)</th>
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<tbody>
<tr>
<td>Small</td>
<td>Between $30,000 and $70,000</td>
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<tr>
<td>Medium</td>
<td>Between $70,000 and $150,000</td>
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<td>Large</td>
<td>Greater than $150,000</td>
</tr>
</tbody>
</table>

1Chemical Engineering Department
2Department of Veterinary Microbiology and Pathology
3Department of Veterinary and Comparative Anatomy, Pharmacology and Physiology
4Electrical and Computer Engineering Department

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CHEMICAL ENGINEERING EDUCATION
use of the terms interdisciplinary, multidisciplinary, crossdisciplinary, transdisciplinary, and others, when describing research across disciplines, is widespread. Recently, Castri [6] suggested a set of precise definitions for the above terms which is based on the level of cooperation among researchers. These definitions, reproduced in Figure 1 (with minor changes), have minimized the confusion. Multidisciplinary research involves several disciplines, usually at the same hierarchical level, without any demand for cooperation. In most cases interaction occurs only during the final stages of the project through editorial integration of the findings. Crossdisciplinary work is characteristic of projects that are problem-focused, where one discipline interacts with others for what those disciplines can offer toward achieving a solution. The project described in this paper fits into this category. Interdisciplinary research, on the other hand, tends to be characterized by the dominance of a common view. This type of cooperation may involve more than one hierarchical level and usually results in new concepts. One example that fits into this category is the work of Barry Richmond, a neurobiologist with the National Institute of Mental Health, and Lance Optican, a biomedical engineer with the National Eye Institute. This interdisciplinary team has come up with a complex mathematical theory (the multiplex filter hypothesis) that challenges scientific orthodoxy by proposing that visual nerves transmit information by multiplexed, encoded signals [7]. This work has the potential of replacing the current way of thinking about the brain. Finally, transdisciplinary efforts involve multilevel interactions that lead to an entire common purpose system. A typical example is the development and deployment of military aircraft [8].

Recently, Castri suggested a set of precise definitions for the terms [interdisciplinary, multidisciplinary, crossdisciplinary, transdisciplinary, and others] which is based on the level of cooperation among researchers. These definitions (with minor changes) have minimized the confusion. A

<table>
<thead>
<tr>
<th>TERM</th>
<th>MODEL</th>
<th>HIERARCHICAL LEVELS</th>
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<tr>
<td>Multidisciplinarity</td>
<td>Scientific</td>
<td>Technological</td>
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<tr>
<td>Crossdisciplinarity</td>
<td>Scientific</td>
<td></td>
</tr>
<tr>
<td>Interdisciplinarity</td>
<td>Technological</td>
<td>Scientific</td>
</tr>
<tr>
<td>Transdisciplinarity</td>
<td>Planning</td>
<td>Policy making</td>
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</table>

FIGURE 1. Models of increasing cooperation and coordination of research management. (Used by permission from the International Science Policy Foundation.)

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project of this magnitude involves all the levels from scientific to policy-making and demands extensive cross-interactions.

In the next section a specific example of an ongoing crossdisciplinary effort between the authors is presented, from which general principles will be extracted on how to initiate and conduct such research.

NEURON-BASED SENSOR RESEARCH PROJECT

The project rationale is presented below. A detailed description of findings are reported elsewhere [9].

Justification

The major problems in reliably determining \textit{in vitro} or \textit{in vivo} concentrations of antibodies or antigens, and for that matter any hormone, protein, ion, toxin, drug, or hazardous substance, are the lack of fast, reusable, and accurate sensing devices. To date, many solutions have been tried [10-18], yet most are still unsatisfactory. In this project, a new approach to sensing is being investigated in which the long term goals are to develop biochips which will be used to monitor electrical activity of neurons and later, excitable synthetic membranes on exposure to analytes. The proposed sensing devices will allow one to take advantage of the specificity, sensitivity, and speed of response characteristic of neurons.

Neurons are the primary nervous system components for processing and transmitting information. An example of a differentiated neuroblastoma (a tumorous nerve cell), cultured in our laboratory, is shown in Figure 2. Some of the processes (axons) receive, while others send, information. Nerve cell membranes contain receptors for neurotransmitters and other chemical species. Receptor/neurotransmitter binding events may lead to the activation of second messenger compounds within the cell, or to the opening or closing (gating) of specific ion channels (e.g., Na\(^+\), K\(^+\) or Ca\(^{2+}\)). The opening of the channels results in ion passage that changes the electrical state of the neuron which in many cases affects neuron electrical properties like action potential (AP) characteristics. For electrically active cells, the channels are voltage sensitive and can be caused to open or close by changing the transmembrane potential through applied current pulses [19].

To achieve a solution to the problem outlined above within a reasonable economic timeframe, we assembled a crossdisciplinary team of engineers and biologists. The engineers brought a systems approach to the project, with a clear view of how the final product should be implemented. The biologists brought essential basic information on the general methodology used to study neurons. To demonstrate proof of concept, neurons from a fresh water snail, \textit{Limnea stagnalis}, were used with alcohols as model analytes (methods and results reported are limited to the initial studies).

Methods and Interpretation of Results

A schematic of the experimental set up is shown in Figure 3. The visceral and right parietal ganglia (a mass of tissue containing nerve cells) were removed from the snail, \textit{Limnea stagnalis}, using the methods of Byerly and Hagiwara [20]. The ganglia were transferred to a continuous flow recording chamber and exposed to varying concentrations of ethanol (0.2-1.0
The methods described above emphasize the need in this project of crossing disciplines. For example, dissecting of the snail to remove the ganglia and intracellular recording are operations neurobiologists perform routinely. On the other hand, for decades engineers have been designing and working with devices capable of processing digital information such as that produced by neuronal firing events.

**FIGURE 4.** Effects of ethanol on the firing frequency in Linnea neurons (stimulating current was 0.8 nA).

![Graph showing effects of ethanol on firing frequency](image)

$M$) in saline solutions. Random cells were impaled with glass micro-electrodes and stimulated to produce APs by passage of current through a bridge circuit from the preamplifier. Signals were monitored using the storage oscilloscope and stored for later analysis on the video recorder. Cells selected for analysis were limited to those which regularly induced spike discharges of amplitudes greater than 50 mV. Repetitive firing rate was based on the interspike intervals of the first four APs, for cells induced by passage of a 1.0 S current pulse with a 0.25 Hz repetition rate.

Responses of different neurons were compared by normalizing firing frequency values to the baseline (no alcohol) response at a given current level and plotting the results as a function of concentration. Some cells showed excitatory effects with increasing concentration, as show in Figure 4. The higher the ethanol concentration, the higher the firing frequency. In Figure 5, plots of normalized firing frequency versus ethanol concentration with 95% confidence interval bands on the mean values, shows three distinct categories. Group 1 with a strong excitatory response, Group 2 with a weaker response, and Group 3 with no response. Linear correlation between analyte concentration and a property of a neuron demonstrates in a preliminary way the feasibility of the sensor concept. More basic and applied work is currently being conducted to demonstrate an expanded scope of applications and to explain the mechanism involved in the sensing process.

**PROJECT FUNDING**

Typically an investigator with a problem looks for new methods or solutions from another discipline, or may alternatively have a novel solution in need of a problem. For the neuron biosensor project, one of us
(BVW) recognized that advances in biosensing technology would require the systematic study of biological chemical sensing. The results obtained from such studies would provide the insights needed to design highly sophisticated detection and signal transmission devices that mimic those present in living systems (e.g., the olfactory system). To verify the concept, suitable techniques for studying neuron behavior were needed. Faculty members who traditionally study neurons were needed for a crossdisciplinary team. A group was identified with expertise in spinal cord neurophysiology, having laboratory facilities with intracellular recording equipment similar to that shown in Figure 3. A proposal was put together for preliminary studies with the main intent of obtaining pilot data to demonstrate the concept.

Crossdisciplinary ideas such as the one in this paper depart dramatically from the current knowledge base and contain substantial uncertainties concerning appropriate methods and outcome. Most systems for selecting university research projects for funding tend to favor proposals with logical and systematic extensions of current knowledge. Such proposals are less risky, tend to have easily predictable outcomes, and are relatively easy to defend. Therefore, the new and innovative crossdisciplinary projects may have difficulty surviving the conventional peer review process. At this point one has to identify a funding source that can entertain exploratory research projects. Table 2 contains a non-exhaustive list of such programs known to the authors. Some of the programs are specifically designed for this purpose.

The neuron-based chemical sensor project was first funded as a NSF Expedited Award for Novel Research at a $30,000 level for 1986/87. Additional funds of $94,000 were obtained from the Washington Technology Center (WTC) for the 1987-1989 biennium as well as a $12,400 grant from the WSU College of Engineering. WTC funds are provided on a matching basis to encourage faculty of universities in the State of Washington to obtain extramural resources in research areas of critical importance to the State.

### TABLE 2

**Possible Sources of Support for Risky Proposals**

<table>
<thead>
<tr>
<th>Sponsoring Agency</th>
<th>Program</th>
<th>Contact</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Science Foundation</td>
<td>Expedited Awards for Novel Research</td>
<td>Engineering Director NSF Washington, DC 20550</td>
<td>• for exploratory research of high but unproven potential for future advances</td>
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<td></td>
<td></td>
<td></td>
<td>• non-renewable funding up to $30,000</td>
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<td></td>
<td></td>
<td></td>
<td>• does not require external review</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• to be re-evaluated after 1988/89</td>
</tr>
<tr>
<td>National Science Foundation</td>
<td>Research Initiation Awards</td>
<td>Engineering Director NSF Washington, DC 20550</td>
<td>• designed to encourage faculty to begin their careers and to make an academic career more attractive</td>
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<tr>
<td></td>
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<td></td>
<td>• funding up to $60,000 for 24 months</td>
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<td></td>
<td></td>
<td></td>
<td>• multiple investigator proposals not eligible</td>
</tr>
<tr>
<td>National Science Foundation</td>
<td>Presidential Young Investigator Awards</td>
<td>Engineering Director NSF Washington, DC 20550</td>
<td>• provides cooperative research support for the most outstanding and promising young science and engineering faculty</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>• nominations originate from department chairs</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• minimum of $25,000 and up to $37,000 in matching funds, which comes to a maximum possible total of $100,000/year, for five years</td>
</tr>
<tr>
<td>Engineering Foundation</td>
<td>Engineering Research Initiation Grants</td>
<td>Dr. R.E. Emmert, Exec Dir. AICHE, United Eng. Cent. 345 East 47th St. New York, NY 10017</td>
<td>• for initiating research for new full time engineering faculty without research support</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• support limited to $20,000</td>
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<td></td>
<td></td>
<td></td>
<td>• crossdisciplinary projects encouraged</td>
</tr>
<tr>
<td>National Institute of Health</td>
<td>Biotech. Research Training</td>
<td>Dr. H. Landsdell Federal Building Room 916 Bethesda, MD 20892</td>
<td>• This program has recently been initiated in response to the enormous growth of the biotechnology industry that has resulted in critical shortages of experts in areas such as biochemical separations and engineering.</td>
</tr>
<tr>
<td>State Biotechnology and/or Technology Centers</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td>• several states have set up centers to support local efforts in biotechnology. However, the nature of the centers varies greatly. Each has a different focus and source of support and set of programs. Some are designed to support business and create new companies. A survey of 40 state-supported biotechnology centers in 28 states was conducted by the Biotechnology Information Program of the North Carolina Biotechnology Center in the fall of 1987.</td>
</tr>
<tr>
<td>Not For-Profit and For-Profit Corporations</td>
<td>University Exploratory Research (P &amp; G Co.)</td>
<td>Procter and Gamble Co. Miami Valley PO Box 389707 Cincinnati, OH 45238</td>
<td>• focuses on proposals that depart dramatically from current knowledge base that entail substantial uncertainty</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• support up to $150,000 for three years</td>
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<td></td>
<td></td>
<td></td>
<td>• not renewable after the three-year period</td>
</tr>
<tr>
<td>Local University Grant and Research Offices</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td>• Several universities have monies that are available internally for limited support. The graduate or grants office puts out announcements for such competitions.</td>
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</table>

**CHEMICAL ENGINEERING EDUCATION**
on successful completion of the first phase, a proposal has been submitted to WTC for funding for the next biennium (1989-91). Two additional proposals have also been submitted to NSF: one to the Biotechnology Program to support the present group’s effort and another to the Emerging Technology Program for an inter-university program with the University of Washington to support a broader based microsensor effort. If these proposals are funded, our project will advance from a small to a medium sized program as defined in Table 1.

PROPOSAL WRITING

Once the funding source(s) is/are identified, it is important that contact is made with the program director(s) to obtain their input on the suitability of the proposal. The next task is writing the proposal—the following procedure worked well for us. First, a tentative table of contents was generated by the ChE group, clearly identifying the parts of the proposal to be written by each participating discipline. Then the participants were asked to write those sections consistent with their expertise. These were circulated one to two weeks before a meeting was held to merge the sections, and after the meeting, the chemical engineering group had the responsibility of preparing a first draft. We have found that this approach solves two key problems associated with proposal writing in a crossdisciplinary environment. First, any misunderstandings regarding approach, paradigms, or jargon are resolved at the outset. Second, consistent terminology and style of writing are adopted since the integration of the proposal components is entrusted to one individual. After preparation of the first draft, the usual procedures for proposal preparation are followed. These include distribution to each participant to check for logical progression of ideas, appropriateness of experimental design to the problem solution, and clarity of experimental protocols and general editing, followed by a meeting to incorporate the new changes prior to preparation of the final copy.

OBSTACLES TO GETTING THE WORK DONE

Although the literature is replete with do’s and don’ts regarding the management of crossdisciplinary projects [21 & 22], there is a paucity of practical suggestions to obviate some of the frequently listed obstacles. In attempting to address this problem, we have limited our discussion to those aspects with which we have had experience.

Language or Jargon

During the proposal writing stages, it is important to remember that credibility must be maintained among reviewers who are aware of the specific disciplines united in the proposal. Therefore, well-known terms and concepts must be used. Because of this, the integration of different language and jargon becomes a problem and it usually surfaces at this point. Some researchers have asserted that jargon should be eliminated [23], but this cannot happen quickly since it takes time to learn another ‘discipline language’. However, efforts have to be made to minimize confusion. For newly formed groups frequent discussions, querying of co-workers, and exchange of relevant papers serve as short term solutions. On a long term basis, participating in a relevant course offered by the co-workers in the other disciplines makes a big difference. For example, three of us (BVW, WSK and RSS) attended a course, “Advanced Neurophysiology,” offered by CDB. Another useful effort, especially for students and postdoctoral associates, is to spend time in the laboratories of the other investigators, under their supervision. For example, WSK does 50% of his experimental work in the laboratory of WCD. The focus of this effort is to develop monoclonal antibodies to differentiated neuroblastoma membrane antigens and to determine the extent of crossreactivity among several cell lines.

Skepticism

In the early stages of a small crossdisciplinary project, there is usually some doubt about the future success of the project. This skepticism has been explained by Bella and Williamson [24] to reflect an understanding of the magnitude of the research problem and the potential inappropriateness of the existing methods. Such an attitude of healthy skepticism is essential. Overconfidence usually reflects a shallow understanding of the important questions. It should be pointed out, however, that extreme skepticism can be disruptive.

Openness to the Evolving Nature of Crossdisciplinary Work

It is unlikely that a principle investigator deliberately identifies the intellectual and social components of a research program organizational pattern in advance. The project organization more often evolves into a stable pattern by trial and error. In our case
the project began with one chemical engineering faculty member (BVW) and two neurophysiologists (CDB and SJF). After a year of initial experimentation, it was determined that if the neurons were to be successfully used as the primary transducers in biosensors, emphasis needed to include fabrication of microdevices that would contain the neuron and the electrical connections. Therefore, electrical engineers (KC and NSD) with expertise in micromachining and integrated circuits technology were invited to join the team. Furthermore, since sensor development efforts are now directed toward biological molecules of economic significance, such as monoclonal antibodies and antigens, an immunologist (WCD) has joined our team. This demonstrates the evolving nature of cross-disciplinary work and the importance of openness to the need of other expertise, which, if ignored, may result in the demise of the project.

**Other Issues**

Based on our experience, frequent team meetings (on top of the standard weekly or bi-weekly meetings between students, postdocs, and their direct supervisors) can be time-consuming. Hence, meetings should be pegged to specific project milestones, as opposed to fixed intervals, in order to avoid unproductive discussions. However, some flexibility should be maintained for emergency meetings as needed. In this regard, availability of modern computers attached to high-speed data networks, such as those donated to numerous universities by AT&T through their University Equipment Donation Program, can temper the inconvenience of emergency meetings. For example, when data are being collected or analyzed, questions that arise which require discussion can be dealt with instantly by all investigators across campus via information sharing workstations.

Also, financial management (especially for work done in more than one laboratory) can lead to time delays. Most universities have straightforward accounting procedures to handle this type of problem. In cases where this is not true, a procedure for billing the project account should be put in place immediately. This will save valuable time. For example, our group needed to immunize rabbits to generate polyspecific serum for testing neuron responses when subjected to antibodies. However, the chemical engineers, in whose hands the budget account resided, lacked clearance to handle live animals, and obtaining this clearance would have taken at least one month. To circumvent this problem, rabbits were purchased through the laboratory of WCD and work was performed under his supervision. The chemical engineering group was later billed for those expenses.

Another obstacle that is often mentioned is conflict of paradigms or concepts. This is potentially the case between scientists (whose focus is mainly on understanding the principle mechanism underlying important processes) and engineers (whose emphasis is mainly on applying existing fundamental knowledge to solving practical problems). Under such circumstances, the best solution might be maintaining good communication links through reviewing progress toward the team’s long-term objectives.

**DISCUSSION**

In this paper we have attempted to describe our experience in initiating and conducting a small biotechnological crossdisciplinary project in a university environment. It is wise to put in perspective the relationship between small university crossdisciplinary projects and the American competitiveness in the global marketplace. The history of science and technology teaches us that most significant developments have occurred as a result of approaches that involved crossing disciplines. In fact, chemical engineering as a discipline is one of these developments. Hence, adaptation of technical information from two disciplines, resulting in a major development, is not new. Reasons for the greater current interest in the subject are better expressed by the NSF in their program announcement for Centers for Crossdisciplinary Research in Engineering, otherwise called Engineering Research Centers (ERC), as follows:

*The need for ERC’s arose from the fact that despite America’s preeminence in science, our competitive position in the international marketplace has been increasingly eroded. Besides the various economic and managerial factors, part of this competitiveness problem can be attributed to the gradual loss of U.S. industrial prowess in turning research discoveries into high-quality, competitive products. Many practitioners and leaders have come to the realization that while American academic engineering has made great strides in basing modern engineering on advanced scientific knowledge and the latest laboratory and computational tools, it has not placed sufficient emphasis on the design of manufacturing processes and products to keep pace with increasingly sophisticated consumer demands around the world. In addition, crossdisciplinary research focused on technological advancements from an engineering systems perspective is needed to better prepare engineering graduates with the diversity and quality of education needed by U.S. industry.*

The National Research Council study on “Chemical
Engineering Frontiers: Needs and Opportunities," chaired by N. R. Amundson of the University of Houston, identified four major areas of opportunity. One of these is the development of new high technology industries that are driven by scientific breakthroughs, including 1) biotechnology, 2) electronic, photonic, and recording materials and devices, and 3) advanced materials. When one focuses on biotechnology, it is not clear whether we at the university are doing enough to "win the war." For example, of the eighteen Engineering Research Centers currently supported by NSF, only one (at the Massachusetts Institute of Technology) addresses a biotechnological aspect (Process Engineering). It appears the process of creating research groups has to begin with small crossdisciplinary projects similar to the one described in this paper, and then grow through the medium and large size levels to finally attain a level where the participants can successfully compete for an ERC grant. The key ingredients to the formation of small projects are the availability of faculty who are willing to cross disciplines and the availability of funds for novel (yet risky) proposals. We believe that a larger pool of funds targeting such studies, which would not be funded through conventional means, may be one step, among many, that could ensure that America maintains the lead it currently enjoys in areas such as biotechnology.

ACKNOWLEDGEMENTS

This study has been made possible by grants from the National Science Foundation (ECE-8609910), the Washington Technology Center (WTC-231555), and the Washington State University Colleges of Engineering and Veterinary Medicine.

REFERENCES

THE ESSENCE OF ENTROPY

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Manhattan, KS 66506

WHO AMONG us, the initiated, has never paused in the midst of a second-law problem to ask, "Is there really such a thing as entropy?" As an unabashed admission of such waverings of faith, this essay attempts to answer the question. It is an examination of paradoxes and putative interpretations of entropy in search of its essence.

THE QUANTUM-STATISTICAL VIEW

Quantization of energy is the salient feature that distinguishes quantum mechanics from classical mechanics. Because a large number of quantum states are available to a single molecule and an enormous number of molecules are present, the number of quantum states accessible to a system of thermodynamic interest is an astronomically large number. In addition to this, the quantum state of the system is continually changing as a result of the motion and collisions of the molecules. It now becomes obvious that to calculate the thermodynamic properties of such a system, some type of statistical averaging process must be used. Fortunately, the extremely large size of the statistical population insures the success of such an averaging procedure and permits certain convenient simplifications in the attendant mathematics.

The average value of any thermodynamic property, \( X \), is calculated in the following manner

\[
\bar{X} = \sum P_i X_i
\]

where \( P_i \) is the probability that the system is in the \( i^{th} \) quantum state, and \( X_i \) is the value of the property when the system occupies the \( i^{th} \) quantum state. In assigning probabilities to quantum states the following rules are followed:

1) Quantum states of equal energy have equal probabilities.
2) The statistical weight of a quantum state depends upon the energy of that state and is proportional to \( \exp(-E/kT) \).

The probability of finding the system in the \( i^{th} \) quantum state with energy \( E_i \) is

\[
P_i = \frac{\exp\left(-\frac{E_i}{kT}\right)}{\sum \exp\left(-\frac{E_j}{kT}\right)}
\]

The summation in the denominator is taken over all quantum states and is a normalizing factor needed to make the sum of the probabilities of all states equal to unity. This sum will be denoted by \( Z \) and is referred to as the partition function.

\[
Z = \sum \exp\left(-\frac{E_i}{kT}\right)
\]

The partition function provides the bridge between statistical mechanics and thermodynamics, for it can be shown that the thermodynamic properties are related in a fairly simple manner to the partition function. The function \( A' \) is defined by

\[
A' = -kT \ln Z
\]

and it can be shown that this function has the properties of the Helmholtz Free Energy.

The statistical entropy can be calculated from Eq. 4 via the thermodynamic relation

\[
S = \frac{A'}{T}
\]

Benjamin G. Kyle is professor of chemical engineering at Kansas State University, where he has enjoyed over thirty years of teaching. He holds a BS from the Georgia Institute of Technology and a PhD from the University of Florida. He has not outgrown an early fascination with thermodynamics and is interested in practically all aspects of the subject. He is the author of a thermodynamics textbook (Prentice-Hall).
\[ S = -\left( \frac{\partial A}{\partial T}\right)_V \]

In terms of the partition function this becomes
\[ S = k \ln Z + kT \left( \frac{\partial \ln Z}{\partial T}\right)_V \]
which after some manipulation can be written in terms of probabilities
\[ S = -k \sum P_i \ln P_i \]
In an isolated system the internal energy is invariant and all quantum states have the same energy level. Thus, our probability rules require that all quantum states be equally probable and
\[ P_i = \frac{1}{\Omega} \]
where \( \Omega \) is the total number of quantum states accessible to the system. When this probability is substituted into Eq. 6, the statistical entropy of an isolated system becomes
\[ S = k \ln \Omega \]
For a spontaneous change occurring in an isolated system we write
\[ S_2 - S_1 = k \ln \frac{\Omega_2}{\Omega_1} \]
and note that the required condition \( S_2 > S_1 \) dictates \( \Omega_2 > \Omega_1 \). This means that the more-stable state is characterized by a larger number of accessible quantum states or a greater number of microscopic configurations (each a quantum state contributing to the number \( \Omega \)) constituting the macroscopic, or thermodynamic, state.

**ENTROPY AS DISORDER**

Thermodynamics requires the existence of a function we call entropy and provides the means of calculating its changes as well as the framework within which it can be advantageously employed. While this is sufficient for any application of thermodynamics, we are nevertheless uncomfortable with abstractions and prefer to attach physical significance to the quantities we deal with. Yet, when the physical representation is strained and leads to ambiguous or erroneous interpretation, the effort is counterproductive. This can often be the case with entropy, especially when it is identified with disorder.

From a molecular viewpoint, the association of positive entropy changes with an increase in disorder seems quite reasonable for phase changes and mixing. For other processes the association is less obvious and for at least one process (the adiabatic crystallization of a subcooled liquid) it fails completely. Unfortunately, order and disorder are not precise objective terms, but carry considerable subjective bias. For example, on consulting a thesaurus one finds many synonyms for order, including regularity, symmetry, harmony, and uniformity. Conceivably, the absence of gradients or differences in potential could be thought to characterize an ordered state. Thus, one who held this view would never realize that these are the conditions of an equilibrium state when told that equilibrium, or a state of maximum entropy, is identified by a maximum of disorder.

In interpreting Eq. 8 it must be remembered that the subscripts 1 and 2 refer to equilibrium states. The accepted microscopic model of an equilibrium state entails complete randomness with regard to molecular motion—chaos or maximum disorder. It therefore seems inappropriate to regard \( \Omega_2 > \Omega_1 \) as representing an increase in disorder when each state represents maximum disorder. All we can say is that \( \Omega \) measures the complexity of our microscopic description of a system, and an increase in \( \Omega \) can be visualized as a spreading of the system over accessible quantum states. The system moves in the direction of more possibilities.

This is not a physically satisfying representation; it is not based on the virtual observables of our microscopic model (e.g., positions and velocities). Its significance is found on a level removed from these in terms of something which can exist only in the mind—the number of quantum states. This concept comes into being only when we move further into the mental realm and begin to translate the physical into the mathematical description. Rudolf Carnap [1] seems to have had this in mind when he stated that the statistical concept of entropy is a logical instead of a physical concept.

**THE GIBBS MIXING PARADOX**

In 1875 Willard Gibbs published his landmark paper "On the Equilibrium of Heterogeneous Sub-
stances.” In this paper he determined the properties of an ideal gas mixture and found the entropy change on mixing to be

$$\Delta S = -R \sum y_i \ln y_i$$  \hspace{1cm} (9)$$

He had firmly established the validity of this expression but Gibbs was not comfortable with the result, and his deliberations over this result have come to be known as the Gibbs Mixing Paradox.

According to Eq. 9, the entropy change on mixing equimolar quantities of two gases is

$$\Delta S = R \ln 2$$

a result that is seen to be independent of the nature of the gases. Gibbs was concerned about the “degree of dissimilarity” between the two gases which could be visualized being made as close to zero as possible. As long as there is some dissimilarity, the entropy of mixing is R \ln 2, but when the “degree of dissimilarity” becomes zero (mixing the same gas), the entropy change is zero. Thus, the entropy of mixing depends not on the “degree of dissimilarity,” but only on whether any dissimilarity exists. It is this “either-or” situation which constitutes the Gibbs Mixing Paradox.

The usual mixing process is carried out with no recovery of work, and because the heat of mixing is zero, there is no exchange of heat with the surroundings. In fact, there is no external change to indicate that the process has occurred. An ordinary mixing of the same gas could not be distinguished experimentally from the mixing of different gases, although an entropy change occurs in the latter case and not the former. Thus, while Eq. 9 was determined in an indirect, but rigorous, thermodynamic manner, we have seen that the entropy of mixing exhibits curious behavior, and further, we have no means of experimental verification.

Insight into the curious behavior of entropy can be found by considering distinguishable spatial configurations. This can be illustrated with the lattice model of solutions [3]. Here one interprets $\Omega_1$ and $\Omega_2$ in Eq. 8 as the number of spatial arrangements or lattice configurations before and after mixing. Before mixing there is but one configuration, and $\Omega_1$ is unity. After mixing the number of configurations is

$$\Omega_2 = \frac{(N_A + N_B)!}{N_A! N_B!}$$

With these values of $\Omega_1$ and $\Omega_2$ Eq. 8 can be reduced to Eq. 9. Although the lattice model is more appropriate to liquids, we note that Eq. 9 also gives the entropy of mixing in an ideal liquid solution, and thus we may expect that the entropy of mixing gases arises from similar configurational considerations. There are more distinguishable spatial arrangements available, hence a larger number of quantum states available, to a mixture than to a pure gas. The only factor determining the entropy of mixing is the distinguishability of the particles of portion A from the particles of portion B. A reason for this will be proposed later.

**THE GIBBS INDISTINGUISHABILITY PARADOX**

Eq. 5 may be used to calculate the entropy of an ideal gas once the partition function has been formulated. The only type of energy possessed by a monatomic ideal gas is kinetic energy and because the energy levels, $E_i s$, are extremely close together, $E$ can be closely approximated as a continuum, and the summation in Eq. 3 can be replaced by an integral. Omitting the particulars of the calculation, the partition function can be obtained straightforwardly and is

$$Z = V^N \left(\frac{2\pi k}{h^2 m T}\right)^{3N/2}$$  \hspace{1cm} (10)$$

The entropy may be obtained by the substitution of Eq. 10 into Eq. 5

$$S = kN \left(\ln V + \frac{3}{2} \ln \left(\frac{2\pi k m T}{h^2}\right) + \frac{3}{2}\right)$$  \hspace{1cm} (11)$$

Entropy is an extensive property, but, unfortunately, not according to Eq. 11. For the simple operation of combining two $\frac{1}{2}$-mol quantities of the same gas, this equation yields

$$\Delta S = N k \ln 2 = R \ln 2$$

We have already seen that this is the entropy of mixing different gases, but we know that there is no entropy change on mixing the same gas. This problem is sometimes identified as the Gibbs paradox although it is really a special case of the mixing paradox [4].

The problem was resolved by Gibbs in 1902 by the ad hoc correction of dividing the partition function of Eq. 10 by $N!$—the number of permutations involving $N$ distinguishable entities. This results in the following expression for the entropy
\[ S = kN \left( \ln \frac{\mathcal{V}}{N} + \frac{3}{2} \ln \left( \frac{2\pi k m T}{\hbar^2} \right) + \frac{5}{2} \right) \] (12)

Eq. 12 satisfies the condition that the entropy be an extensive property. It has become known as the Sakur-Tetrode equation and has been verified experimentally.

Today, in the quantum age of physics, it is customary to specify whether or not the constituent particles of a system are distinguishable. However, in the classical age of Gibbs' day, the particles of an ideal monatomic gas were assumed independent with their motion described by classical mechanics. While there was certainly an impossible computational difficulty in providing the exact description prescribed by the equations of classical mechanics, there was no doubt that in principle, particles could be traced and thus retained their identity. While still holding to the principle of the distinguishability of particles, Gibbs justified the adventitious insertion of \( N! \) into Eq. 10 by saying that the interchange of like particles should be of no statistical consequence.

It is interesting to note that the ad hoc adjustment is unnecessary in the case of the internal energy. Combination of Eqs. 4 and 5 shows that the internal energy is

\[ U = kT^2 \left( \frac{\partial \ln Z}{\partial T} \right)_v \] (13)

Regardless of whether the partition function of Eq. 10 is divided by \( N! \), the result is the same and correctly shows that \( U \) is linear in \( N \). Thus, of the two basic thermodynamic properties, only the entropy requires an adjustment of classical thought by introducing the concept of indistinguishable particles.

Again, it appears that in order to deal successfully with entropy it is necessary to go a step beyond a description of the system in terms of virtual observables. Instead of a model involving physical quantities, we have included factors such as distinguishability which arise from our mathematical treatment and exist only in the mind of the model maker. The focus has been shifted from the system to our representation of the system—again, a move from the physical to the logical realm.

**ENTROPY, INFORMATION, AND SUBJECTIVITY**

A major tenet of the philosophical underpinning of science is the concept of objective observation—an observer independent of the observed object. An unquestioning acceptance of this concept had prevailed until recent developments in modern physics suggested that it may not be applicable at the sub-atomic level. Specifically, Bohr's concept of complementarity and Heisenberg's uncertainty principle recognize that the behavior of a system cannot be properly described until the presence of observing instruments is accounted for. This implies that the observer is part of the system and has encouraged in some quarters the advancement of a subjective philosophic view [5].

The concept of objective observation has been challenged only in the sub-atomic realm; it is still firmly entrenched outside this realm, and is unquestioned when dealing with systems of thermodynamic interest. Nevertheless, there exists a tendency to take a subjective viewpoint in regard to entropy when interpreted microscopically from the perspective of information. Recently, Denbigh and Denbigh [2] have convincingly shown that no formal relation exists between thermodynamic entropy, a physical quantity, and a term labeled entropy that arises from information theory and is a logical quantity [6]. However, because the entropy-information association considerably predates information theory [7], it will probably remain well-ingrained despite the Denbighs' efforts.

The putative view interprets the condition \( \Omega_2 > \Omega_1 \) corresponding to an increase in entropy as an observer's loss of information about the microscopic state of the system. Accordingly, one reasons that there are more possibilities in state 2 and therefore the increase in \( \Omega \) implies more uncertainty or a loss of information. This view presents two difficulties. First, because \( \Omega \) is not a virtual observable quantity, it is doubtful that an observer could have access to this type of information. The information associated with \( \Omega \) concerns not the system, but our description of the system. Second, it is unreasonable to believe that \( \Delta S \), a thermodynamic property change which depends on objectively determined macrostates, could also depend on microscopic information gained or lost by an observer.

In an effort to blunt the last criticism, Jaynes [8] has suggested the following carefully worded definition of information.

The entropy of a thermodynamic system is a measure of the degree of ignorance of a person whose sole knowledge about its microstate consists of the values of the macroscopic quantities \( X_i \) which define its thermodynamic state. This is a completely 'objective' quantity, in the sense that it is a function only of the \( X_i \) and does not depend on anybody's personality. There is then no reason why it cannot be measured in the laboratory.

Here, one wonders what type of knowledge of the
While entropy seems the most subjective property, the whole field of thermodynamics is uncomfortably redolent of human intent. The requirement of subscripts on its partial derivatives reminds us that the system is being constrained, or manipulated. Many of its variables lack easy physical correspondence...

microstate is lacking. Virtual observables such as position and velocity would be subject to continual fluctuation, and hence an instantaneous determination of these would be of no practical value. The identification of quantum states and the knowledge of their corresponding probabilities would be of obvious value, but these, as we have also shown with \( \Omega \), are not virtual observables but rather are mental constructs which allow us to model the system. It would appear then that this unpossessed knowledge of the microstate is either unusable or is an artifact of the microscopic model we have constructed to represent the macrostate of the system. We surmise that Jaynes is speaking of useful microscopic knowledge, but must note that there is a double dose of subjectivity here. First, we have introduced quantities such as \( \Omega \) which are mental constructs that relate to our description of the system rather than to the system itself. Second, we now say that the macroscopic behavior of the system, as reflected in the value of the entropy, is dependent on the extent of our knowledge of these model parameters.

Let us test Jaynes' interpretation through the use of Eq. 8 that relates the statistical entropy change to \( \Omega_2/\Omega_1 \). It would seem that a definite informational value could be assigned to the knowledge of \( \Omega \) regardless of its numerical value. We are not asking which microstate the system is presently in, which would have informational value dependent on the numerical value of \( \Omega \), but rather how many microstates are possible. We are dealing with a model parameter, \( \Omega \), and therefore the knowledge embodied in its determination should be constant and independent of the macrostate of the system. If this is so, then there is no change in knowledge of microstates between any two macrostates and the informational entropy change is always zero. We reach the same conclusion by noting that the number of position coordinates and velocity components is always \( 6N \) regardless of the macroscopic state of the system—a constant amount of microscopic knowledge. Thus, the concept of entropy as a measure of microscopic information is inconsistent as well as extremely subjective.

THE ESSENCE OF ENTROPY

The interpretation of entropy in terms of information leads to an extreme subjective position and must be rejected. On the other hand, it must be confessed that entropy is more subjective, or less objective, than other properties of matter. This is because the existence of a human mind must be assumed before an entropy change for a macroscopic system can be evaluated or, as we have already seen, a microscopic interpretation can be appreciated. In the case of the evaluation of an entropy change, it is first necessary to devise a reversible path and then perform the calculation from the definition

\[
\Delta S = \int \frac{\text{d}Q_{\text{rev}}}{T}
\]

This is not an act of rote calculation but is rather a process of mental creation.

While entropy seems the most subjective property, the whole field of thermodynamics is uncomfortably redolent of human intent. The requirement of subscripts on its partial derivatives reminds us that the system is being constrained, or manipulated. Many of its variables lack easy physical correspondence and only seldom is a thermodynamic variable evaluated except as a means of calculating some more "practical" quantity. In fact, it has been suggested that its various applications can be integrated into a coherent whole only by recognizing thermodynamics to be "a means of extending our experimentally gained knowledge of a system or as a framework for viewing and correlating the behavior of the system" [9]. Clearly, the emphasis is on utility. Having arisen from efforts to exploit rather than to observe nature, the laws of thermodynamics cannot be completely cleansed of their earthy taint and are often embarrassing to the scientist for their lack of intellectual purity. Uneasiness with this anthropomorphic quality of thermodynamics has been confessed by P. W. Bridgman, one of its foremost thinkers [10]:

It must be admitted, I think, that the laws of thermodynamics have a different feel from most of the other laws of the physicist. There is something more palpably verbal about them—they smell more of their human origin. The guiding motif is strange to most of physics: namely, a capitalizing of the universal failure of human beings to construct perpetual motion machines of either the first or the second kind. Why should we expect nature to be interested either positively or negatively in the purposes of human beings, particularly purposes of such an unblushingly economic tinge?
Modern science begins with experience, which is by nature local and transitory, and by ratiocination arrives at laws that are considered universal and timeless. These laws usually connect quantities which are not directly related to our sensory experience, even to the extent of being only mental constructs that are often contrary to common sense. (Recall Newton's uneasiness over the need for a gravitational force which acts at a distance.) Thus, the formulations of science are considered to be in the realm of the pure intellect. In recognizing this, Sir Arthur Eddington has referred to the enterprise of science as "mind-stuff" and has expanded this theme most eloquently [11]:

We have found that where science has progressed the farthest, the mind has but regained from nature that which the mind put into nature. We have found a strange footprint on the shores of the unknown. We have devised profound theories, one after another, to account for its origin. At last, we have succeeded in reconstructing the creature that made the footprint. And Lo! it is our own.

Paraphrasing Eddington with the incorporation of Bridgman’s thought, we could say that in the case of thermodynamics, that which the mind has regained from nature reflects the economic, or human, quality of the input.

Entropy’s human scent can be traced to its derivation. Essential to both the conventional Carnot-cycle proof and the mathematically more elegant Caratheodory proof [12] is the concept of a reversible process. Seldom is this even an approximation of reality. It is a concept understandable only to economic man desiring to reap the most from his attempted taming of nature and can not be considered scientifically objective. Yet, only in this context can an unambiguous interpretation of entropy be found: the total entropy change measures the lost work when a process falls short of this human-scented, value-laden standard. Something on which we have placed value has been lost. This carries over into the microscopic view where the valued commodity is either order or information.

The mixing paradox exposes the incongruity of the value-laden macroscopic view and a naive microscopic view of entropy. The microscopic description of an ideal gas in purely physical terms leads to Eq. 11 and to the conclusion that the process of mixing the same gas is no different from the mixing of different gases. It is the economic or utilitarian aspect of the situation, the work of separation, that discriminates between the processes and forces the inclusion of N! into the microscopic description. The reversal of the mixing process requires separational work when the gases are different. However, we have neither the need nor the ability to exactly reverse the mixing of portions of the same gas and therefore need expend no separational work. Because the minimum work of separation is TAS for ideal gas mixtures, there must therefore be no entropy change on mixing the same gas. The microscopic description is brought into conformance with the macroscopic situation by requiring indistinguishability of particles. Thus, a utilitarian consideration, human in origin, requires the insertion of a logical (or human-scented) term into the microscopic model.

In failing to examine nature in a disinterested or completely objective manner, we have obtained a quantity, the entropy, which is not completely objective and which can be understood only by an appeal to the human mind. We can only conclude that entropy is neither completely subjective nor completely objective. Its existence can be publicly agreed upon and its consistent use has great utility, but its existence does not seem to be independent of the human mind. It may not be an intrinsic property of matter, but rather an objectively defined quantity which, for our convenience, we may treat as a property. Born of the unnatural union of wish and reality, entropy is objective enough to be useful in dealing with the physical world, but subjective enough that a purely physical interpretation lies beyond our grasp.

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6. This is also the conclusion of Carnap, reference 1
I feel that I benefit the most from research-oriented courses. At the beginning of such a course, the instructor...introduces the basic principles and refers to the current development of the subject.

artificial intelligence techniques to the control of chemical processes. Interdisciplinary in nature, it allows knowledge of, for example, computer science and electrical engineering to be extensively applied to chemical processes. So far, I have completed 25 regular graduate courses which are distributed among three majors: eight courses on fundamentals of chemical engineering, eight on artificial intelligence and software engineering, and nine on control engineering and system science.

I have studied aggressively and worked hard in course work, since I knew that these courses would directly benefit my thesis research. I took them not only to satisfy credit requirements, but also to fulfill the perceived needs of my research. In fact, several research publications resulted directly from the course work since I was able to immediately see practical applications in novel areas and, also, I maintained an excellent academic record.

I feel that I benefit the most from research-oriented courses. At the beginning of such a course, the instructor (usually an expert on the subject he teaches) introduces the basic principles and refers to the current development of the subject. Meanwhile, the key literature and references are distributed to students. To fulfill the course requirements, every student has to read the literature carefully, do homework assignments, take quizzes or examinations, present a key paper orally, and finish a research project which is followed by a final report. Needless to say, such a course is usually very demanding and time-consuming; however, it gives us practical experience in research and brings us to the frontier of the related subject quickly. There is another significant benefit that comes from a research-oriented course. From it we can learn how to do research: through search and review of published literature, research topic selection, oral presentation, conducting the project, and technical writing. Each of these steps is exactly a principal element in the research process, isn't it?
I believe universities provide the best environment for learning. Facing choices from among many useful courses offered, we are unable to take all of the courses we need. However, auditing will help us to partially solve this problem. I usually audit one course each semester. Although I do not do the work of this course in detail, I still learn the basic principles, definitions, and terminologies.

I am also interested in attending and participating in various research seminars. I often attend two or three seminars each week, in different departments and universities. The speakers at the seminars are usually famous scholars or young experts in specialized fields. They can provide us with the newest developments and the most advanced techniques. We also have the opportunity to extend our knowledge, to acquire new motivation, to exchange ideas, and to develop oral communication skills [1].

**THESIS RESEARCH TOPIC**

I believe that the most important element in pursuit of a PhD degree is thesis research. The main purpose of thesis research is to learn how to do research work and how to solve problems independently [2]. Notably, research topic selection plays a key role in thesis research. Three aspects should be taken into account in topic selection: 1) personal research interest and academic background, 2) adviser's suggestions, and 3) available research facilities.

I feel that research interest is the most crucial factor. In a survey on doctoral dissertation experience, it has been found that personal interest is rated as the most important factor influencing research topic choice [3]. If you love the job you are doing, you will be happy and won't care about how difficult it is. On the other hand, as we know, no one can succeed at the work to which he does not bring great confidence and enthusiasm.

The choice of research topic also needs to fit our academic background to a certain extent. Graduate training is the continuation of undergraduate study. Undergraduate study provides us with a broad and basic academic background, while graduate education trains us to do independent research. Our past experience and knowledge will pave the way for us to go toward the final goal.

Unfortunately, many graduate students do not approach this aspect seriously. They simply ask their adviser: "What topic is available for me?" Rather, I believe that the fundamental question is: What is the purpose of a PhD dissertation? As stated in many graduate program brochures, it should reflect original, independent research, and is supposed to contribute new knowledge to the field in some way [2]. Here, originality means "nothing similar to prior work." Independent research requires that we work on our own at each step of the project, including topic selection.

If we tell the adviser first what we want to do, this will show that we are approaching our subject with maturity and motivation, and it will help the adviser understand our interests and potential. At this moment, the adviser can encourage and guide us and suggest appropriate avenues of research [4]. An important factor is that we are stimulated to gain creativity by such a training process. When we do not have enough experience, our ideas are often imperfect, i.e., wrong in some aspects, even unrealistic. But one should not forget that new ideas sometimes seem crazy at first [5, 6].

**SELF-LEARNING AND INDEPENDENT RESEARCH**

In recent years, much attention has been focused on the need to train creative engineers for industry and society. Though there are many different definitions of creativity, everyone agrees that "creativity (whatever it is) involves the ability to put things (words, concepts, methods, devices) together in novel ways" [5].

I believe that creativity may also include 1) self-learning capability and 2) independent research capability. Learning is a process that never ends. Earning a PhD is by no means the end of learning; it is a new beginning [7].

In our professional career, it is normal for us to meet with new problems, some of which are not directly related to our past knowledge and experience. The self-learning capability enables us to learn and obtain what we need in solving these problems. It also provides a free hand for us to carry out independent research.

The main objective of dissertation research is to help us gain a generally valuable experience, particularly by teaching us the skills of independent research [3]. Independent research capability consists of two subsets: the capability to analyze problems and the capability to solve problems. The former can help us
identify and formulate problems, while the latter may provide us the means to find the solution to the problems.

In my experience, the secret of learning how to do independent research can be summarized as “plan big, start small.” “Plan big” means that we should establish a big, even fantastic research goal. All of the research efforts we make are for society’s future needs, not for the past. “Plan big” addresses our research into the important investigations of science and technology. “Start small” suggests that, at the start, we should initiate a small project in order to obtain the necessary experience. Meanwhile, early successes, even small ones, can strengthen our confidence and stimulate our struggle toward the final objective.

As I complete my graduate study, I find that I have gained sound training in both academic study and independent research capability. This professional training went through four stages. These stages have a chronological progress, but the main distinctions separating them are not based on time divisions, but on the demonstration of independent research capability.

**Stage 1: Implementation**

Much of my work before graduate school was based on the detailed implementation of certain research efforts. I finished undergraduate study, and was able to implement published theoretical algorithms under my supervisor’s advice. These included carrying out experiments, repairing instrumentation, setting up equipment, and writing computer programs based on available algorithms. My adviser assigned the project and gave me details about related techniques; then I worked on it. I became truly involved in research and gained hands-on experience.

**Stage 2: Programming**

An obvious benefit at this level is that I began doing independent research. My adviser suggested research directions and provided some important technical details. I sought a possible solution for realization of these ideas. I initiated small research topics, obtained the needed information by self-instruction, carried out research, and wrote technical papers for publication. I had learned how to translate an original idea into a prototype capable of practical application. Typical examples are: implementation of CAD packages [8], development of prototype expert systems [9, 10], proof or discovery of new algorithms and criteria [9, 11], and others.

**Stage 3: Problem-Solving**

This stage is the key to graduate research [2]. At this stage my goal was no longer only to deal with a detailed research project or to get new design criteria. With encouragement from the adviser, I applied my knowledge to the formulation of general methodology for problem-solving, defined research directions and long-term topics, helped the adviser prepare research proposals, and made the important discovery.

Several significant research efforts were generated at this stage, such as an integrated intelligent system architecture for developing high-performance intelligent systems [12], adaptive feedback testing system for enhancing expert system reliability [9], and graphic simulation as a new knowledge representation technique [13]. These projects focused on developing problem-solving methodology and universal configuration. Beyond the significant theoretical results and practical applications, the most important factor is the demonstration of creativity.

**Stage 4: Administration**

The experience gained at this stage is very important for developing management and leadership skills. It is usually obtained from post-doctoral training or independent work as a university faculty member.

I was appointed as a supervisor for developing an Intelligent Control Laboratory, an NSF-sponsored project. I began to supervise junior graduate students and learned how to cooperate with other professors. We are now working together in order to solve the tough problems in biochemical process control and to establish university/industry cooperation research. We are planning to develop a new interdisciplinary graduate program to train chemical engineers in the most advanced techniques and to build a comprehensive research center for intelligent control.

I have begun to extend our research into other engineering fields, and I have also become involved more in technical management and leadership, such as helping prepare “Decision Systems Engineering,” a new interdisciplinary graduate program to design a PhD curriculum, consulting for business and industrial companies, and working as session chairman in international conferences.

**ADVISER’S FUNCTION**

The PhD adviser plays a key role in dissertation research. The faculty adviser guides our study of the fundamentals, explains why we do research, how to do research, and instills in us feelings of confidence. Professor Amundson summarized all of these aspects...
and pointed out, "The relationship between PhD advisor and graduate student is a unique kind of relationship that obtains nowhere else . . ." [4].

Without question, my adviser, Dr. Jiang, Associate Professor of Chemical and Biochemical Engineering and Director of Intelligent Control Laboratory, deserves much credit for my success. I feel fortunate to be able to work in Dr. Jiang's research team. He has given me the opportunity to learn, and has trained me as a professional scholar. Throughout my training process, I have greatly benefitted from his advice, suggestions, patient observations, help, strong encouragement, and support. Chronologically, Dr. Jiang has trained me through three different stages.

The first stage: Infancy

When I started dissertation research, I lacked the necessary depth of knowledge and experience. I used to show uncertainty or no confidence in research. Dr. Jiang always tried to find the positive elements and proofs of success in my progress, such as getting an "A" in a course, understanding a new algorithm, and so on. He always gave me encouragement. This stage can be called the infancy of my “plan big.”

The second stage: Cold War Period

As my professional career progressed, especially in the transition from the programming stage to the problem-solving stage, I thought I had achieved a little success in both academic background and dissertation research. I was satisfied with certain detailed technique results and implementations. However, I limited myself from going more deeply into scientific research and prevented myself from seeking problem-solving methodology. Seeing this happen, Dr. Jiang changed his attitude. He criticized my work severely—even my success. It was a difficult time for me, like a “cold war” in my graduate study. However, I was awakened from my ignorance, began more serious study and thinking, and improved the quality of my research.

The third stage: Maturity

After I gained more experience in independent research, Dr. Jiang let me become more involved in administrative activities in order to develop my leadership skills. Through my training in administrative capability, I feel that I have become more mature. In less than four years of graduate study. I took 25 courses, audited 8 courses, published over 40 research papers in reputable journals and conference proceedings, attended 18 scientific and technical conferences, and was chosen as session chairman at international conferences. Also, I was awarded a Doctoral Excellence Fellowship by the Rutgers Graduate School, received a MS degree in computer science, and will soon complete a PhD in engineering. In addition, I have travelled in 47 American states and 5 foreign countries and have visited most of the research-oriented universities in the USA and Canada to obtain information and knowledge from my colleagues. I now have enough confidence and experience to believe that when I complete my doctorate, I can be successful either in academia or industry [4].

CONCLUSIONS

Briefly the main tenets of my view of graduate study are:

- The main objective of graduate study is to learn how to do independent research and how to foster creativity. Creativity includes self-learning and independent research capabilities, which can help one to analyze problems and then to formulate solutions for them.
- How to begin independent research? "Plan big, start small."
- The dissertation adviser plays a very important role in our professional training process.
- Personal interest is a key to selecting research topics.
- Course work is more fruitful when it is directly related to dissertation research rather than simply fulfilling curriculum requirements.

My future plans are to improve my communication skills, to expand both my academic background and research, to learn more, to do more, and to succeed in my professional career. I feel that I have a contribution to make to science, technology, and humanity. It is my goal to make that contribution.

ACKNOWLEDGMENT

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ChE book reviews

MOLECULAR THERMODYNAMICS FOR NONIDEAL FLUIDS
by L. L. Lee
Butterworths, 80 Montvale Ave., Stoneham, MA 02180; $52.95 (1988)

Reviewed by Keith E. Gubbins
Cornell University

This is a graduate level book aimed at presenting modern statistical mechanical methods to engineers and applied scientists. Until the early 1970's these rigorous methods were only applicable to gases, crystalline solids, and simple liquids such as argon, and so are of limited value to engineers. Over the last fifteen years or so they have been extended to include nonspherical and polar molecules, electrolytes, nonideal solutions, and most recently, a wide variety of surface phenomena. There have been rapid developments in perturbation and integral equation theories, in computer simulation methods, and in scattering experiments that provide information about the molecular or atom-atom correlations functions. These powerful methods are gradually replacing the more empirical methods that engineers have traditionally used, and so a book of this sort is welcome. The only other books aimed at engineers of which I am aware are Reed and Gubbins' Applied Statistical Mechanics (now out of print and in some respects out of date) and Lucas' Angewandte Statistische Thermodynamik (so far only available in the original German, although an English translation is planned for late 1989 or early 1990).

The coverage of the book is good. The first three chapters deal with introductory material—classical and quantum mechanics, the ensembles, and ideal gases. The remainder of the book covers more recent developments in the theory of liquids (Chapters 4-12, 14), the molecular dynamics simulation method (Chapter 13), and adsorption of solids (Chapter 15). There are useful appendices dealing with intermolecular forces, and giving computer programs for the solution of integral equations and molecular dynamics calculations. The parts dealing with liquids are thorough and well done. They cover the distribution functions and integral equations for fluids of polar and nonspherical molecules and not just spherical molecules as in many other books. There are quite detailed accounts of the integral equation and perturbation theory methods, including chapters on hard body fluids, Lennard-Jones fluids, polar fluids, electrolytes, and site-site model fluids.

As a teaching text the book has some drawbacks. The introduction to the ensembles is quite brief and lacks illuminating examples, figures, or much in the way of physical interpretation, so most students experiencing this material for the first time will find it hard going. There is a similar problem with the treatment of the distribution functions in Chapter 4. The chapter on molecular dynamics is well done, but for students it would be helpful to have some simpler examples or programs, and some discussion of the Monte Carlo method, which is easier to program for a beginner. It would have been helpful to have had more illustrative examples and well thought out questions at the end of chapters. The layout of the book is rather poor, with too much print on each page and poorly reproduced figures, making it somewhat difficult to read.

In conclusion, this is an up-to-date summary of a rapidly developing field that is aimed at an engineering audience. It will be especially useful to graduate students and other researchers as an introduction to the subject, but will need to be supplemented if it is used as a teaching text. □
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J. H. MASLIYAH, Ph.D. (British Columbia): Transport Phenomena, Numerical Analysis, Particle-Fluid Dynamics

A. E. MATHER, Ph.D. (Michigan): Phase Equilibria, Fluid Properties at High Pressures, Thermodynamics

W. K. NADER, Dr. Phil. (Vienna): Heat Transfer, Transport Phenomena in Porous Media, Applied Mathematics

K. NANDAKUMAR, Ph.D. (Princeton): Transport Phenomena, Process Simulation, Computational Fluid Dynamics

F. D. OTTO, Ph.D. (Michigan), DEAN OF ENGINEERING: Mass Transfer, Gas-Liquid Reactions, Separation Processes, Heavy Oil Upgrading


D. B. ROBINSON, Ph.D. (Michigan), PROFESSOR EMERITUS: Thermal and Volumetric Properties of Fluids, Phase Equilibria, Thermodynamics

J. T. RYAN, Ph.D. (Missouri): Energy Economics and Supply, Porous Media


S. E. WANKE, Ph.D. (California-Davis), CHAIRMAN: Heterogeneous Catalysis, Kinetics

R. K. WOOD, Ph.D. (Northwestern): Process Simulation, Identification and Modelling, Distillation Column Control

For further information contact
CHAIRMAN
DEPARTMENT OF CHEMICAL ENGINEERING
UNIVERSITY OF ALBERTA
EDMONTON, CANADA T6G 2G6
THE UNIVERSITY OF ARIZONA
TUCSON, AZ

The Chemical Engineering Department at the University of Arizona is young and dynamic, with a fully accredited undergraduate degree program and M.S. and Ph.D. graduate programs. Financial support is available through fellowships, government grants and contracts, teaching, and research assistantships, traineeships and industrial grants. The faculty assures full opportunity to study in all major areas of chemical engineering. Graduate courses are offered in most of the research areas listed below.

THE FACULTY AND THEIR RESEARCH INTERESTS ARE:

MILAN BIER, Professor, Director of Center for Separation Science*
Ph.D., Fordham University, 1950
Protein Separation, Electrophoresis, Membrane Transport

HERIBERTO CABEZAS, Asst. Professor
Ph.D., University of Florida, 1984
Liquid Solution Theory, Solution Thermodynamics, Polyelectrolyte Solutions

WILLIAM P. COSART, Assoc. Professor, Assoc. Dean
Ph.D., Oregon State University, 1973
Heat transfer in Biological Systems, Blood Processing

EDWARD J. FREEH, Research Professor
Ph.D., Ohio State University, 1958
Process Control, Computer Applications

JOSEPH F. GROSS, Professor
Ph.D., Purdue University, 1966
Boundary Layer Theory, Pharmacokinetics, Fluid Mechanics and Mass Transfer in the Microcirculation, Biochemistry

ROBERTO GUZMAN, Asst. Professor
Ph.D., North Carolina State University, 1988
Protein Separation, Affinity Methods

GARY K. PATTERSON, Professor and Head
Ph.D., University of Missouri-Rolla, 1966
Rheology, Turbulent Transport, Numerical Modeling of Transport, Bioreactors

THOMAS W. PETERSON, Professor
Ph.D., California Institute of Technology, 1977
Atmospheric Modeling of Aerosol Pollutants, Particulate Growth Kinetics, Combustion Aerosols, Microcontamination

ALAN D. RANDOLPH, Professor
Ph.D., Iowa State University, 1962
Simulation and Design of Crystallization Processes, Nucleation Phenomena, Particulate Processes, Explosives Initiation Mechanisms

THOMAS R. REHM, Professor
Ph.D., University of Washington, 1960
Mass Transfer, Process Instrumentation, Packed Column Distillation, Computer Aided Design

FARHANG SHADMAN, Professor
Ph.D., University of California-Berkeley, 1972
Reaction Engineering, Kinetics, Catalysis, Coal Conversion

JOST O. L. WENDT, Professor
Ph.D., Johns Hopkins University, 1968
Combustion Generated Air Pollution, Nitrogen and Sulfur Oxide Abatement, Chemical Kinetics, Thermodynamics, Interfacial Phenomena

DON H. WHITE, Professor
Ph.D., Iowa State University, 1949
Polymers Fundamentals and Processes, Solar Energy, Microbial and Enzymatic Processes

DAVID WOLF, Visiting Professor
D.Sc., Technion, 1962
Energy, Fermentation, Mixing

*Center for Separation Science is staffed by four research professors, several technicians, and several postdocs and graduate students. Other research involves 3-D electrophoresis, cell culture, electro cell fusion, and electro fluid dynamic modelling.

Tucson has an excellent climate and many recreational opportunities. It is a growing modern city of 450,000 that retains much of the old Southwestern atmosphere.

For further information, write to

Dr. Jost O. L. Wendt
Graduate Study Committee
Department of Chemical Engineering
University of Arizona
Tucson, Arizona 85721

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University of Arkansas

Department of Chemical Engineering

Graduate Study and Research Leading to MS and PhD Degrees

FACULTY AND AREAS OF SPECIALIZATION

Michael D. Ackerson (Ph.D., U. of Arkansas)
Biochemical Engineering, Thermodynamics

Robert E. Babcock (Ph.D., U. of Oklahoma)
Water Resources, Fluid Mechanics, Thermodynamics, Enhanced Oil Recovery

Edgar C. Clausen (Ph.D., U. of Missouri)
Biochemical Engineering, Process Kinetics

James L. Gaddy (Ph.D., U. of Tennessee)
Biochemical Engineering, Process Optimization

Jerry A. Havens (Ph.D., U. of Oklahoma)
Irreversible Thermodynamics, Fire and Explosion Hazards, Assessment, Dense Gas Dispersion

William A. Myers (M.S., U. of Arkansas)
Natural and Artificial Radioactivity, Nuclear Engineering

W. Roy Penney (Ph.D., Oklahoma State University)
Process Engineering, Process Development

Thomas O. Spicer (Ph.D., U. of Arkansas)
Computer Simulation, Dense Gas Dispersion

Charles Springer (Ph.D., U. of Iowa)
Mass Transfer, Diffusional Processes

Charles M. Thatcher (Ph.D., U. of Michigan)
Mathematical Modeling, Computer Simulation

Jim L. Turpin (Ph.D., U. of Oklahoma)
Fluid Mechanics, Biomass Conversion, Process Design

Richard K. Ulrich (Ph.D., U. of Texas)
Microelectronics Materials and Processing, Superconductors

J. Reed Welker (Ph.D., U. of Oklahoma)
Risk Analysis, Fire and Explosion Behavior and Control

LOCATION
The University of Arkansas at Fayetteville, the flagship campus in the six-campus system, is situated in the heart of the Ozark Mountains and offers students a unique blend of urban and rural environments. Fayetteville is literally surrounded by some of the most outstanding outdoor recreation facilities in the nation, but it is also a dynamic city and serves as the center of trade, government, and finance for the region. The city and University offer a wealth of cultural and intellectual events.

FACILITIES
The Department of Chemical Engineering occupies more than 40,000 sq. ft. in the new Bell Engineering Center, a $30-million state-of-the-art facility, and an additional 20,000 sq. ft. of laboratories at the Engineering Research Center.

FINANCIAL AID
Graduate students are supported by fellowships and research or teaching assistantships.

FOR FURTHER DETAILS CONTACT
Dr. W. Roy Penney, Professor and Head
Department of Chemical Engineering
3202 Bell Engineering Center
University of Arkansas
Fayetteville, AR 72701
CHEMICAL ENGINEERING
Graduate Studies

THE FACULTY

R. T. K. BAKER (University of Wales, 1966)
R. P. CHAMBERS (University of California, 1965)
C. W. CURTIS (Florida State University, 1976)
J. A. GUIN (University of Texas, 1970)
L. J. HIRTH (University of Texas, 1958)
A. KRISHNAGOPALAN (University of Maine, 1976)
Y. Y. LEE (Iowa State University, 1972)
G. MAPLES (Oklahoma State University, 1967)
R. D. NEUMAN (Institute of Paper Chemistry, 1973)
T. D. PLACEK (University of Kentucky, 1976)
C. W. ROOS (Washington University, 1951)
A. R. TARRER (Purdue University, 1973)
B. J. TATARCHUK (University of Wisconsin, 1981)

For Information and Application, Write
Dr. R. P. Chambers, Head
Chemical Engineering
Auburn University, AL 36849-5127

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Molecular Dynamics
Process Design
Process Control

For additional information write to:
Graduate Coordinator
Department of Chemical Engineering, 350 CB
Brigham Young University
Provo, Utah 84602
Tel: (901) 378-2586
The Department offers graduate programs leading to the M.Sc. and Ph.D. degrees in Chemical Engineering (full-time) and the M.Eng. degree in Chemical Engineering or Petroleum Reservoir Engineering (part-time) in the following areas:

- Thermodynamics - Phase Equilibria
- Heat Transfer and Cryogenics
- Catalysis, Reaction Kinetics and Combustion
- Multiphase Flow in Pipelines
- Fluid Bed Reaction Systems
- Environmental Engineering
- Petroleum Engineering and Reservoir Simulation
- Enhanced Oil Recovery
- In-Situ Recovery of Bitumen and Heavy Oils
- Natural Gas Processing and Gas Hydrates
- Computer Simulation of Separation Processes
- Computer Control and Optimization of Bio/Engineer Processes
- Biotechnology and Biorheology

Fellowships and Research Assistantships are available to qualified applicants.

FOR ADDITIONAL INFORMATION WRITE
DR. A. K. MEHROTRA, CHAIRMAN GRADUATE STUDIES COMMITTEE
DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING
UNIVERSITY OF CALGARY, CALGARY, ALBERTA, CANADA T2N 1N4

The University is located in the City of Calgary, the Oil capital of Canada, the home of the world famous Calga Stampede and the 1988 Winter Olympics. The City combines the traditions of the Old West with the sophistication a modern urban center. Beautiful Banff National Park is 110 km west of the City and the ski resorts of Banff, Lake Louise, and Kananaskis areas are readily accessible. In the above photo the University Campus is shown with the Olympic Oval and the student residences in the foreground. The Engineering complex is on the left of the picture.
offers graduate programs leading to the Master of Science and Doctor of Philosophy. Both programs involve joint faculty-student research as well as courses and seminars within and outside the department. Students have the opportunity to take part in the many cultural offerings of the San Francisco Bay Area, and the recreational activities of California's northern coast and mountains.

FACULTY

Alexis T. Bell (Chairman)
Harvey W. Blanch
Elton J. Cairns
Arup K. Chakraborty
Douglas S. Clark
Morton M. Denn
Alan S. Foss
Simon L. Goren
David B. Graves
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C. Judson King
Scott Lynn
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John S. Newman
Eugene E. Petersen
John M. Prausnitz
Clayton J. Radke
Jeffrey A. Reimer
David S. Soane
Doros N. Theodorou
Charles W. Tobias
Michael C. Williams

RESEARCH INTERESTS

ENVIRONMENTAL PROTECTION
KINETICS AND CATALYSIS
THERMODYNAMICS
POLYMER TECHNOLOGY
ELECTROCHEMICAL ENGINEERING
PROCESS DESIGN AND DEVELOPMENT
SURFACE AND COLLOID SCIENCE
BIOCHEMICAL ENGINEERING
SEPARATION PROCESSES
FLUID MECHANICS AND RHEOLOGY
ELECTRONIC MATERIALS PROCESSING

PLEASE WRITE:
Department of Chemical Engineering
UNIVERSITY OF CALIFORNIA
Berkeley, California 94720
Faculty

BELL, Richard L.
University of Washington, Seattle - Mass transfer phenomena on non-ideal trays, environmental transport, biochemical engineering.

BOULTON, Roger
University of Melbourne - Chemical engineering aspects of fermentation and wine processing, fermentation kinetics, computer simulation and control of operational processes.

HIGGINS, Brian G.

JACKMAN, Alan P.
University of Minnesota - Biological kinetics and reactor design, kinetics of ion exchange, environmental solute transport, heat and mass transport at air-water interface, hemodynamics and fluid exchange.

KATZ, David F.
University of California, Berkeley - Biological fluid mechanics, biorheology, cell biology, image analysis.

McCOY, Benjamin J.
University of Minnesota - Chemical reaction engineering — adsorption, catalysis, multiphase reactors; separation processes — chromatography, ion exchange, supercritical fluid extraction.

McDONALD, Karen
University of Maryland, College Park - Distillation control, control of multivariable, nonlinear processes, control of biochemical processes, adaptive control, parameter and state estimation.

PALAZOGLU, Ahmet
Rensselaer Polytechnic Institute - Process control, process design and synthesis.

POWELL, Robert L.
The Johns Hopkins University - Rheology, fluid mechanics, properties of suspensions and physiological fluids.

RYU, Dewey D.Y.
Massachusetts Institute of Technology - Kinetics and reaction engineering of biochemical and enzyme systems, optimization of continuous bioreactor, biocatalysis of bioactively active compounds, biochemical and genetic engineering, and renewable resources developments.

SMITH, J.M.
Massachusetts Institute of Technology - Transport rates and chemical kinetics for catalytic reactors, studies by dynamic and steady-state methods in slurry, trickle-bed, single pellet, and fixed-bed reactors.

STROEVE, Pieter
Massachusetts Institute of Technology - Transport with chemical reaction, biotechnology, rheology of heterogeneous media, thin film technology, interfacial phenomena, image analysis.

WHITAKER, Stephen
University of Delaware - Drying porous media, transport processes in heterogeneous reactors, multiphase transport phenomena in heterogeneous systems.

Course Areas

- Applied Kinetics & Reactor Design
- Applied Mathematics
- Biomedical/Biochemical Engineering
- Environmental Transport
- Fluid Mechanics
- Heat Transfer
- Mass Transfer
- Process Design & Control
- Process Dynamics
- Rheology
- Separation Processes
- Thermodynamics
- Transport Phenomena in Multiphase Systems

More Information

The Graduate Group in Biomedical Engineering is now housed within the Department of Chemical Engineering. Further information and application materials for either program (Chemical Engineering or Biomedical Engineering) and financial aid may be obtained by writing:

Graduate Admissions
Department of Chemical Engineering
University of California, Davis
Davis, CA 95616

The city of Davis is adjacent to the campus and within easy walking or cycling distance. Both furnished and unfurnished one- and two-bedroom apartments are available. Married student housing, at reasonable cost, is located on-campus.

Davis and Vicinity

The campus is a 20-minute drive from Sacramento and just an hour away from the San Francisco Bay Area. Outdoor enthusiasts may enjoy water sports at nearby Lake Berryessa, skiing and other alpine activities in the Lake Tahoe Bowl (2 hours away). These recreational opportunities combine with the friendly informal spirit of the Davis campus and town to make it a pleasant place in which to live and study.
CHEMICAL ENGINEERING AT

UCLA

PROGRAMS

UCLA's Chemical Engineering Department offers a program of teaching and research linking fundamental engineering science and industrial needs. The department's national leadership is demonstrated by the newly established Engineering Research Center for Hazardous Substance Control. This center of advanced technology is complemented by existing programs in Environmental Transport Research and Biotechnology Research and Education.

Fellowships are available for outstanding applicants. A fellowship includes a waiver of tuition and fees plus a stipend.

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

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• FACULTY AND RESEARCH INTERESTS •

L. GARY LEAL Ph.D. (Stanford) (Chairman) • Fluid Mechanics; Transport Phenomena; Polymer Physics.
PRAMOD AGRAWAL Ph.D. (Purdue) • Biochemical Engineering, Fermentation Science.
SANJOY BANERJEE Ph.D. (Waterloo) • Two-Phase Flow, Chemical & Nuclear Safety, Computational Fluid Dynamics, Turbulence.
DAN G. CACUCI Ph.D. (Columbia) • Computational Engineering, Radiation Transport, Reactor Physics, Uncertainty Analysis.
OWEN T. HANNA Ph.D. (Purdue) • Theoretical Methods, Chemical Reactor Analysis, Transport Phenomena.
SHINICHI ICHIKAWA Ph.D. (Stanford) • Adsorption and Heterogeneous Catalysis.
JACOB ISRAELACHVILI Ph.D. (Cambridge) • Surface and Interfacial Phenomena, Adhesion, Colloidal Systems, Surface Forces.
FRED F. LANGE Ph.D. (Penn State) • Powder Processing of Composite Ceramics; Liquid Precursors for Ceramics; Superconducting Oxides.
JOHN E. MYERS Ph.D. (Michigan) (Professor Emeritus) • Boiling Heat Transfer.
ROBERT G. RINKER Ph.D. (Caltech) • Chemical Reactor Design, Catalysis, Energy Conversion, Air Pollution.
THEOFANOUS Ph.D. (Minnesota) • Nuclear and Chemical Plant Safety, Multiphase Flow, Thermalhydraulics.
W. HENRY WEINBERG Ph.D. (U.C. Berkeley) • Surface Chemistry; Heterogeneous Catalysis; Electronic Materials.

PROGRAMS AND FINANCIAL SUPPORT

The Department offers M.S. and Ph.D. degree programs. Financial aid, including fellowships, teaching assistantships, and research assistantships, is available. Some awards provide limited moving expenses.

THE UNIVERSITY

One of the world's few seashore campuses, UCSB is located on the Pacific Coast 100 miles northwest of Los Angeles and 330 miles south of San Francisco. The student enrollment is over 16,000. The metropolitan Santa Barbara area has over 150,000 residents and is famous for its mild, even climate.

For additional information and applications, write to:

Professor L. Gary Leal
Department of Chemical & Nuclear Engineering
University of California
Santa Barbara, CA 93106
CHEMICAL ENGINEERING  
at the  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
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• FACULTY •
Frances H. Arnold  
James E. Bailey  
John F. Brady  
George R. Gavalas  
Konstantinos P. Giapis  
Julia A. Kornfield  
Manfred Morari  
C. Dwight Prater (Visiting)  
John H. Seinfeld  
Fred H. Shair  
Nicholas W. Tschoegl (Emeritus)

• RESEARCH INTERESTS •
Aerosol Science  
Applied Mathematics  
Atmospheric Chemistry and Physics  
Biocatalysis and Bioreactor Engineering  
Bioseparation  
Catalysis  
Chemical Vapor Deposition  
Combustion  
Colloid Physics  
Computational Hydrodynamics  
Fluid Mechanics  
Materials Processing  
Microelectronics Processing  
Polymer Science  
Process Control and Synthesis  
Protein Engineering  
Statistical Mechanics of Heterogeneous Systems

for further information, write:

Professor John F. Brady  
Department of Chemical Engineering  
California Institute of Technology  
Pasadena, California 91125

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Paul Frattini (Microbiology and Biophysics)
Rakesh Jain (Tumor Microcirculation)

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John Anderson (Membrane and Colloid Transport Phenomena)
Dennis Prieve (Colloid & Surface Science)
Myung Jhon (Polymer Science)

♣ COMPUTER AIDED DESIGN AND OPTIMIZATION
Arthur Westerberg (Design Research)
Ignacio Grosman (Process Synthesis and Design)
Lorenz Biegler (Process Simulations and Optimizations)
Gary Powers (Process Synthesis and Design)
Gregory McRae (Mathematical Modeling and Environmental Engineering)

♦ ADVANCED MATERIALS PROCESSING
Edmond Ko (Heterogenous Catalysis and Semiconductor Processing)
Paul Sides (Electrochemical Engineering and Semiconductor Processing)
William Hammack (Oxide glasses, Infrared Optical Materials)

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Herbert Toor (Heat & Mass Transfer)

Carnegie Mellon

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Carnegie Mellon University
Pittsburgh, Pa 15213-3890

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Faculty and specializations:
- Robert J. Adler, Ph.D. 1959, Lehigh University - Particle separations, mixing, acid gas recovery
- John C. Angus, Ph.D. 1960, University of Michigan - Redox equilibria, thin carbon films, modulated electroplating
- Coleman B. Brosilow, Ph.D. 1962, Polytechnic Institute of Brooklyn - Adaptive inferential control, multi-variable control, coordination algorithms
- Robert V. Edwards, Ph.D. 1968, Johns Hopkins University - Laser anemometry, mathematical modelling, data acquisition
- Donald L. Feke, Ph.D. 1981, Princeton University - Colloidal phenomena, ceramic dispersions, fine-particle processing
- Nelson C. Gardner, Ph.D. 1966, Iowa State University - High-gravity separations, sulfur removal processes
- Uziel Landau, Ph.D. 1975, University of California (Berkeley) - Electrochemical engineering, current distributions, electrodeposition
- Chung-Chiun Liu, Ph.D. 1968, Case Western Reserve University - Electrochemical sensors, electrochemical synthesis, electrochemistry related to electronic materials
- J. Adin Mann, Jr., Ph.D. 1962, Iowa State University - Surface phenomena, interfacial dynamics, light scattering
- Syed Qutubuddin, Ph.D. 1983, Carnegie-Mellon University - Surfactant systems, metal extraction, enhanced oil recovery
- Robert F. Savinell, Ph.D. 1977, University of Pittsburgh - Electrochemical engineering, reactor design and simulation, electrode processes

Train in:
- Electrochemical engineering
- Laser applications
- Mixing and separations
- Process control
- Surface and colloids

For more information contact:
The Graduate Coordinator
Department of Chemical Engineering
Case Western Reserve University
University Circle
Cleveland, Ohio 44106

CASE WESTERN RESERVE UNIVERSITY
CLEVELAND, OHIO 44106
GRADUATE STUDY in 
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Amy Ciric
Joel Fried
Stevin Gehrke
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Daniel Hershey
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Dean of the Graduate School
Clarkson University
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The Faculty

Charles H. Barron, Jr.
John N. Beard, Jr.
Dan D. Edie
Charles H. Gooding

James M. Haile
Douglas E. Hirt
Stephen S. Melsheimer
Joseph C. Mullins

Amod A. Ogale
Richard W. Rice
Mark C. Thies

Programs lead to the M.S. and Ph.D. degrees. Financial aid, including fellowships and assistantships, is available.

For Further Information
For further information and a descriptive brochure, write:

Graduate Coordinator
Department of Chemical Engineering
Earle Hall
Clemson University
Clemson, South Carolina 29634
UNIVERSITY OF COLORADO, BOULDER

• RESEARCH INTERESTS •

Alternate Energy Sources
Biotechnology and Bioengineering
Heterogeneous Catalysis
Coal Gasification and Combustion
Enhanced Oil Recovery
Fluid Dynamics and Fluidization
Interfacial and Surface Phenomena
Low Gravity Fluid Mechanics and
Materials Processing
Mass Transfer
Membrane Transport and Separations
Numerical and Analytical Modeling
Process Control and Identification
Semiconductor Processing
Surface Chemistry and Surface Science
Thermodynamics and Cryogenics
Thin Film Science
Transport Processes

• FACULTY •

DAVID E. CLOUGH, Professor, Associate Dean
for Academic Affairs
Ph.D., University of Colorado, 1975

ROBERT H. DAVIS, Associate Professor
Ph.D., Stanford University, 1983

JOHN L. FALCONER, Professor
Ph.D., Stanford University, 1974

R. IGOR GAMOW, Associate Professor
Ph.D., University of Colorado, 1967

HOWARD J. M. HANLEY, Professor Adjoint
Ph.D., University of London, 1963

DHINAKAR S. KOMPALA, Assistant Professor
Ph.D., Purdue University, 1984

WILLIAM B. KRANTZ, Professor
Ph.D., University of California, Berkeley, 1968

RICHARD D. NOBLE, Research Professor
Ph.D., University of California, Davis, 1976

W. FRED RAMIREZ, Professor
Ph.D., Tulane University, 1965

ROBERT L. SANI, Professor
Director of Center for Low Gravity
Ph.D., University of Minnesota, 1963

KLAUS D. TIMMERHAUS, Professor and Chairman
Ph.D., University of Illinois, 1951

RONALD E. WEST, Professor
Ph.D., University of Michigan, 1958

FOR INFORMATION AND APPLICATION, WRITE TO
Chairman, Graduate Admissions Committee
Department of Chemical Engineering
University of Colorado
Boulder, Colorado 80309-0424

FALL 1989
THE FACULTY AND THEIR RESEARCH

A. J. KIDNAY, Professor and Head; D.Sc., Colorado School of Mines. Thermodynamic properties of gases and liquids, vapor-liquid equilibria, cryogenic engineering.

J. H. GARY, Professor Emeritus; Ph.D., Florida. Petroleum refinery processing operations, heavy oil processing, thermal cracking, visbreaking and solvent extraction.

V. F. YESAVAGE, Professor; Ph.D., Michigan. Vapor liquid equilibrium and enthalpy of polar associating fluids, equations of state for highly non-ideal systems, flow calorimetry.

E. D. SLOAN, JR., Professor; Ph.D. Clemson. Phase equilibrium measurements of natural gas fluids and hydrates, thermal conductivity of coal derived fluids, adsorption equilibria, education methods research.

R. M. BALDWIN, Professor; Ph.D., Colorado School of Mines. Mechanisms and kinetics of coal liquefaction, catalysis, oil shale processing, supercritical extraction.

M. S. SELIM, Professor; Ph.D., Iowa State. Heat and mass transfer with a moving boundary, sedimentation and diffusion of colloidal suspensions, heat effects in gas absorption with chemical reaction, entrance region flow and heat transfer, gas hydrate dissociation modeling.

A. L. BUNGE, Associate Professor; Ph.D., Berkeley. Membrane transport and separations, mass transfer in porous media, ion exchange and adsorption chromatography, in place remediation of contaminated soils, percutaneous absorption.

R. L. MILLER, Research Assistant Professor; Ph.D., Colorado School of Mines. Liquefaction co-processing of coal and heavy oil, low severity coal liquefaction, oil shale processing, particulate removal with venturi scrubbers, supercritical extraction.

J. F. ELY, Adjunct Professor; Ph.D., Indiana. Molecular thermodynamics and transport properties of fluids.

For Applications and Further Information On M.S., and Ph.D. Programs, Write
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Colorado School of Mines
Golden, CO 80401
Location:
CSU is situated in Fort Collins, a pleasant community of 80,000 people located about 65 miles north of Denver. This site is adjacent to the foothills of the Rocky Mountains in full view of majestic Long's Peak. The climate is excellent with 300 sunny days per year, mild temperatures and low humidity. Opportunities for hiking, camping, boating, fishing and skiing abound in the immediate and nearby areas. The campus is within easy walking or biking distance of the town's shopping areas and its new Center for the Performing Arts.

Degrees Offered:
M.S. and Ph.D. programs in Chemical Engineering

Financial Aid Available:
Teaching and Research Assistantships paying a monthly stipend plus tuition reimbursement

Research Areas:
Alternate Energy Sources
Biotechnology
Chemical Thermodynamics
Chemical Vapor Deposition
Computer Simulation and Control
Environmental Engineering
Fermentation
Food Engineering
Hazardous Waste Treatment
Polymeric Materials
Porous Media Phenomena
Rheology
Semiconductor Processing
Solar Cooling Systems

For Applications and Further Information, write:
Professor Vincent G. Murphy
Department of Agricultural and Chemical Engineering
Colorado State University
Fort Collins, CO 80523
Graduate Study in Chemical Engineering
M.S. and Ph.D. Programs for Scientists and Engineers

Faculty and Research Areas

<table>
<thead>
<tr>
<th>Name</th>
<th>Research Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>THOMAS F. ANDERSON</td>
<td>statistical thermodynamics, phase equilibria, separations</td>
</tr>
<tr>
<td>JAMES P. BELL</td>
<td>structure and properties of polymers</td>
</tr>
<tr>
<td>DOUGLAS J. COOPER</td>
<td>expert systems, process control, fluidization</td>
</tr>
<tr>
<td>ROBERT W. COUGHLIN</td>
<td>catalysis, biotechnology, surface science</td>
</tr>
<tr>
<td>MICHAEL B. CUTLIP</td>
<td>chemical reaction engineering, computer applications</td>
</tr>
<tr>
<td>ANTHONY T. DIBENEDETTO</td>
<td>polymer science, composite materials</td>
</tr>
<tr>
<td>JAMES M. FENTON</td>
<td>electrochemical engineering, environmental engineering</td>
</tr>
<tr>
<td>G. MICHAEL HOWARD</td>
<td>process dynamics, energy technology</td>
</tr>
<tr>
<td>HERBERT E. KLEI</td>
<td>biochemical engineering, environmental engineering</td>
</tr>
<tr>
<td>JEFFREY T. KOBERSTEIN</td>
<td>polymer morphology and properties</td>
</tr>
<tr>
<td>MONTGOMERY T. SHAW</td>
<td>polymer processing, rheology</td>
</tr>
<tr>
<td>DONALD W. SUNDSTROM</td>
<td>environmental engineering, biochemical engineering</td>
</tr>
<tr>
<td>ROBERT A. WEISS</td>
<td>polymer science</td>
</tr>
</tbody>
</table>

We’ll gladly supply the Answers!

Graduate Admissions
Dept. of Chemical Engineering
Box U-139
The University of Connecticut
Storrs, CT 06268
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William L. Olbricht
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Ferdinand Rodriguez
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Ithaca, NY 14853-5201
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Graduate Advisor
Department of Chemical Engineering
University of Delaware
Newark, Delaware 19716
Modern Applications of Chemical Engineering
at the
University of Florida

Graduate Study Leading to the MS and PhD

FACULTY

TIM ANDERSON • Semiconductor Processing, Thermodynamics
IOANNIS BITSANIS • Molecular Modeling of Interfaces
SEYMOUR S. BLOCK • Biotechnology
RAY W. FAHIEH • Transport Phenomena, Reactor Design
ARTHUR L. FRICKE • Polymers, Pulp & Paper Characterization
GAR HOFUND • Catalysis, Surface Science
LEW JOHNS • Applied Design, Process Control, Energy Systems
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DINESH O. SHAH • Surface Sciences, Biomedical Engineering
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Pradeep K. Agrawal
Yaman Arkun
Sue Ann Bidstrup
Charles A. Eckert
William R. Ernst
Larry J. Forney
Charles W. Gorton
Jeffery S. Hsieh
Paul A. Kohl
Michael J. Matteson
John D. Muzzy
Robert M. Nerem
Gary W. Poehlein
Ronnie S. Roberts
Ronald W. Rousseau
Thanassios Sambanis
Robert J. Samuels
F. Joseph Schork
A. H. Peter Skelland
Jude T. Sommerfeld
D. William Tedder
Amyn S. Teja
Mark G. White
Timothy M. Wick
Jack Winnick
Ajit Yoganathan

Research Interests
Adsorption
Aerosols
Biomedical engineering
Biochemical engineering
Catalysis
Composite materials
Crystallization
Electrochemical engineering
Environmental chemistry
Extraction
Fine particles
Interfacial phenomena

Microelectronics
Physical properties
Polymer science and engineering
Polymerization
Process control and dynamics
Process synthesis
Pulp and paper engineering
Reactor analysis and design
Separation processes
Surface science and technology
Thermodynamics
Transport phenomena

For more information write:
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School of Chemical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0100
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- Enhanced Oil Recovery

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- Vemuri Balakotaiah
- Elmond Claridge
- Abe Dukler
- Demetre Economou
- Ernest Henley
- John Killough
- Dan Luss
- Richard Pollard
- William Prengle
- Raj Rajagopalan
- Jim Richardson
- Cynthia Stokes
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- Richard Willson
- Frank Worley

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FACULTY
Joachim Floess
Ph.D., Massachusetts Inst. of Tech., 1985
Assistant Professor

Richard D. Gonzalez
Ph.D., The Johns Hopkins University, 1965
Professor

John H. Kiefer
Ph.D., Cornell University, 1961
Professor

G. Ali Mansoori
Ph.D., University of Oklahoma, 1969
Professor

Irving F. Miller
Ph.D., University of Michigan, 1960
Professor and Head

Sohail Murad
Ph.D., Cornell University, 1979
Associate Professor, Director of Graduate Studies

John Regalbuto
Ph.D., University of Notre Dame, 1986
Assistant Professor

Satish C. Saxena
Ph.D., Calcutta University, 1956
Professor

Stephen Szepe
Ph.D., Illinois Institute of Technology, 1966
Associate Professor

Raffi M. Turian
Ph.D., University of Wisconsin, 1964
Professor

David Willcox
Ph.D., Northwestern University, 1985
Assistant Professor

RESEARCH AREAS

Transport Phenomena: Slurry transport, multiphase fluid flow and heat transfer, fixed and fluidized bed combustion, indirect coal liquefaction, porous media, membrane transport, pulmonary deposition and clearance, biorheology.

Thermodynamics: Transport properties of fluids, statistical mechanics of liquid mixtures, supercritical fluid extraction/retrograde condensation, asphaltene characterization, bioseparations.

Kinetics and Reaction Engineering: Gas-solid reaction kinetics, diffusion and adsorption phenomena, energy transfer processes, laser diagnostics, combustion chemistry, environmental technology.

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For more information:
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Biotechnology
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- RICHARD A. BEISSINGER (D.E.Sc., Columbia)
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- ALI CINAR (Ph.D., Texas A & M)
  Chemical process control, distributed parameter systems, expert systems
- DIMITRI GIDASPOW (Ph.D., IIT)
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- M. HOSSEIN HARIRI (Ph.D., Manchester-UMIST)
  Bioseparation, flow in porous media and process design
- HENRY R. LINDEN (Ph.D., IIT)
  Energy policy, planning, and forecasting
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  Biochemical engineering, chemical reaction engineering
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  Combustion, high-temperature chemical reaction engineering
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- DARSH T. WASAN (Ph.D., California-Berkeley)
  Interfacial phenomena, separation processes, enhanced oil recovery

APPLICATIONS

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ENGINEERING

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--Membrane Separations
--Particle Morphological Analysis
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--Materials Science
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Iowa City, Iowa 52242
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Iowa 52242.
William H. Abraham
Thermodynamics, heat and mass transport, process modeling

Lawrence E. Burkhart
Fluid mechanics, separation process, ceramic processing

George Burnet
Coal technology, separation processes, high temperature ceramics

John M. Eggebrecht
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Charles E. Glatz
Biochemical engineering, processing of biological materials

Kurt R. Hebert
Applied electrochemistry, corrosion

James C. Hill
Fluid mechanics, turbulence, convective transport phenomena, aerosols

Kenneth R. Jolls
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Terry S. King
Catalysis, surface science, catalyst applications

Maurice A. Larson
Crystallization, process dynamics

Peter J. Reilly
Biochemical engineering, enzyme technology, carbohydrate chromatography

Glenn L. Schrader
Catalysis, kinetics, solid state electronics processing, sensors

Richard C. Seagrave
Biological transport phenomena, biothermodynamics, reactor analysis

Dean L. Ulrichson
Process modeling, simulation

Thomas D. Wheelock
Chemical reactor design, coal technology, fluidization

Gordon R. Youngquist
Crystallization, chemical reactor design, polymerization

For additional information, please write:
Graduate Officer
Department of Chemical Engineering
Iowa State University
Ames, Iowa 50011
Timothy A. Barbari
Ph.D., University of Texas, Austin
Membrane Science
Sorption and Diffusion in Polymers
Polymeric Thin Films

Michael J. Betenbaugh
Ph.D., University of Delaware
Biochemical Kinetics
Insect Cell Culture
Recombinant DNA Technology

Marc D. Donohue
Ph.D., University of California, Berkeley
Equations of State
Statistical Thermodynamics
Phase Equilibria

Joseph L. Katz
Ph.D., University of Chicago
Nucleation
Crystallization
Flame Generation of Ceramic Powders

Robert M. Kelly
Ph.D., North Carolina State University
Process Simulation
Biochemical Engineering
Separations Processes

Mark A. McHugh
Ph.D., University of Delaware
High-Pressure Thermodynamics
Polymer Solution Thermodynamics
Supercritical Solvent Extraction

Geoffrey A. Prentice
Ph.D., University of California, Berkeley
Electrochemical Engineering
Corrosion

W. Mark Saltzman
Ph.D., Massachusetts Institute of Technology
Transport in Biological Systems
Polymeric Controlled Release
Cell-Surface Interactions

W. H. Schwarz
Dr. Engr., Johns Hopkins University
Rheology
Non-Newtonian Fluid Dynamics
Physical Acoustics of Fluids
Turbulence

For further information contact:
The Johns Hopkins University
Chemical Engineering Department
Baltimore, MD 21218
(301) 338-7170
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- Nucleate Boiling
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- Process Control
- Supercomputer Applications
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- Carl E. Locke (Ph.D., Texas)
- James O. Maloney (Ph.D., Penn State)
- Russell B. Mesler (Ph.D., Michigan)
- Floyd W. Preston (Ph.D., Penn State)
- Harold F. Rosson (Ph.D., Rice)
- Marylee Z. Southard (Ph.D., Kansas)
- Randall V. Sparer (Ph.D., Case Western Reserve)
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- George W. Swift (Ph.D., Kansas)
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- G. Paul Willhite (Ph.D., Northwestern)

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Biochemical Engineering
Process Dynamics and Control
Chemical Reaction Engineering
Materials Science
Catalysis and Fuel Synthesis
Process System Engineering
and Artificial Intelligence
Environmental Pollution Control
Fluidization and Solid Mixing
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✓ THE AREA  UK’s 680-acre campus is nestled within the heart of one of America’s most picture-perfect areas, Lexington, and its surrounding Kentucky Bluegrass region. Worthy of note: students here frequently earn their degrees and “stay”- since Lexington is listed as one of the top 10 cities in the country to live, work, raise a family and relax.

✓ THE DEPARTMENT  Bright, well-rounded students, state-of-the-art facilities, substantial funding, and a superb reputation within both academic and industrial circles combine to make UK’s Chemical Engineering department one of the finest in the nation. Not coincidentally, of the 115 U.S. Ph.D. -granting departments, UK’s is one of a select few which has both produced a PYI and has a PYI on its faculty. (See photo above.)

✓ THE FACULTY  UK’s Chemical Engineering faculty (listed herein) is a diverse group of distinguished individuals whose outside interests range from gourmet cooking (Indian and French), gardening and clogging to attending rock concerts, tennis and sailing. On the job, they share an excitement for research, teaching, and discovery that’s remarkably contagious.

<table>
<thead>
<tr>
<th>Faculty</th>
<th>Ph.D. Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>D. Bhattacharyya</td>
<td>Illinois Institute of Technology</td>
</tr>
<tr>
<td>G.F. Crewe</td>
<td>West Virginia</td>
</tr>
<tr>
<td>F.J. Derbyshire</td>
<td>Imperial College</td>
</tr>
<tr>
<td>C.E. Hamrin, Jr.</td>
<td>Northwestern</td>
</tr>
<tr>
<td>G.P. Huffman</td>
<td>West Virginia</td>
</tr>
<tr>
<td>R.I. Kermode</td>
<td>Northwestern</td>
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Quebec, Canada

Ph.D. and M.Sc.
in Chemical Engineering

Research Areas

• CATALYSIS (S. Kaliaguine)
• BIOCHEMICAL ENGINEERING (L. Chaplin, A. LeDuy, R. W. Lencki, J. -R. Moreau, J. Thibault)
• ENVIRONMENTAL ENGINEERING (R. S. Ramalho, C. Roy)
• COMPUTER AIDED ENGINEERING (P. A. Tanguy)
• TECHNOLOGY MANAGEMENT (P. -H. Roy)
• MODELLING AND CONTROL (J. Thibault)
• RHEOLOGY AND POLYMER ENGINEERING (A. Ait-Kadi, L. Chaplin, P. A. Tanguy)
• THERMODYNAMICS (R. S. Ramalho, S. Kaliaguine)
• CHEMICAL AND BIOCHEMICAL UPGRADING OF BIOMASS (S. Kaliaguine, A. LeDuy, C. Roy)
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Le Responsable du Comité d'Admission et de Supervision
Département de génie chimique
Faculté des sciences et de génie
Université Laval
Sainte-Foy, Québec, Canada G1K 7P4

The Faculty

ABDELLATIF AIT-KADI
Ph.D. École Poly. Montréal
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LIONEL CHOPLIN
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Ph.D. École Poly. Montréal
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- biochemical engineering; bioseparations

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- process design & control; distillation

Janice A. Phillips (University of Pennsylvania)
- biochemical engineering; instrumentation/control of bioreactors; mammalian cell culture

William E. Schiesser (Princeton University)
- numerical algorithms & software in chemical engineering

Cesar A. Silebi (Lehigh University)
- separation of colloidal particles; electrophoresis; mass transfer

Leslie H. Sperling (Duke University)
- mechanical & morphological properties of polymers;
  interpenetrating polymer networks

Fred P. Stein (University of Michigan)
- thermodynamic properties of mixtures

Harvey G. Stenger, Jr. (Massachusetts Institute of Technology)
- plasma etching; catalysis; air pollution control

Israel E. Wachs (Stanford University)
- materials synthesis & characterization; surface chemistry;
  heterogeneous catalysis
THE CITY
Baton Rouge is the state capitol and home of the major state institution for higher education – LSU. Situated in the Acadian region, Baton Rouge blends the Old South and Cajun Cultures. The Port of Baton Rouge is a main chemical shipping point, and the city's economy rests heavily on the chemical and agricultural industries. The great outdoors provide excellent recreational activities year round, additionally the proximity of New Orleans provides for superb nightlife, especially during Mardi Gras.

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TO APPLY, CONTACT:
DIRECTOR OF GRADUATE INSTRUCTION
Department of Chemical Engineering
Louisiana State University
Baton Rouge, LA 70803

FACULTY

J.R. COLLIER (Ph.D., Case Institute)
Polymers, Fluid Flow, CAD/CAM

A.B. CORRIPIO (Ph.D., LSU)
Control, Simulation, Computer Aided Design

K.M. DOOLEY (Ph.D., Delaware)
Heterogeneous Catalysis, Reaction Engineering

G.L. GRIFFIN (Ph.D., Princeton)
Heterogeneous Catalysis, Surfaces, Materials Processing

F.R. GROVES (Ph.D., Wisconsin)
Control, Modeling, Separation Processes

D.P. HARRISON (Ph.D., Texas)
Fluid–Solid Reactions, Hazardous Wastes

A.E. JOHNSON (Ph.D., Florida)
Distillation, Control, Modeling

M. HJORTSØ (Ph.D., Univ. of Houston)
Biotechnology, Applied Mathematics

F.C. KNOFP (Ph.D., Purdue)
Computer Aided Design, Supercritical Processing

E. McLAUGHLIN (D.Sc., Univ. of London)
Thermodynamics, High Pressures, Physical Properties

R.W. PIKE (Ph.D., Georgia Tech)
Fluid Dynamics, Reaction Engineering, Optimization

G.L. PRICE (Ph.D., Rice Univ.)
Heterogeneous Catalysis, Surfaces

D.D. REIBLE (Ph.D., Caltech)
Environmental Chemodynamics, Transport Modeling

R.G. RICE (Ph.D., Pennsylvania)
Mass Transfer, Separation Processes

A.M. STERLING (Ph.D., Univ. of Washington)
Transport Phenomena, Combustion

L.J. THIBODEAUX (Ph.D., LSU)
Chemodynamics, Hazardous Waste

D.M. WETZEL (Ph.D., Delaware)
Physical Properties, Hazardous Wastes

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Fluid Mechanics, Rheology, Biochemical Engineering

WILLIAM H. CECKLER Sc.D. (M.I.T.)  
Heat Transfer, Pressing & Drying Operations, Energy from Low BTU Fuels, Process Simulation & Modeling

ALBERT CO Ph.D. (Wisconsin)  
Polymeric Fluid Dynamics, Rheology, Transport Phenomena, Numerical Methods

JOSEPH M. GENCO Ph.D. (Ohio State)  
Process Engineering, Pulp and Paper Technology, Wood Delignification

JOHN C. HASSLER Ph.D. (Kansas State)  
Process Control, Numerical Methods, Instrumentation and Real Time Computer Applications

MARQUITA K. HILL Ph.D. (U.C. Davis)  
Environmental Science, Waste Management Technology

JOHN J. HWALEK Ph.D. (Illinois)  
Liquid Metal Natural Convection, Electronics Cooling, Process Control Systems

ERDOGAN KIRAN Ph.D. (Princeton)  
Polymer Physics & Chemistry, Supercritical Fluids, Thermal Analysis & Pyrolysis, Pulp & Paper Science

DAVID J. KRASKE (Chairman) Ph.D. (Inst. Paper Chemistry)  
Pulp, Paper & Coating Technology, Additive Chemistry, Cellulose & Wood Chemistry

JAMES D. LISIS Ph.D. (Illinois)  
Electrochemical Engineering, Composite Materials, Coupled Mass Transfer

KENNETH I. MUMME Ph.D. (Maine)  
Process Simulation and Control, System Identification & Optimization

HEMANT PENDSE Ph.D. (Syracuse)  
Colloidal Phenomena, Particulate & Multiphase Processes, Porous Media Modeling

EDWARD V. THOMPSON Ph.D. (Polytechnic Institute of Brooklyn)  
Thermal & Mechanical Properties of Polymers, Papermaking and Fiber Physics

DOUGLAS L. WOERNER Ph.D. (Washington)  
Membrane Separations, Polymer Solutions, Colloid & Emulsion Technology

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The spacious campus is situated on 1,200 acres overlooking the Penobscot and Stillwater Rivers. Present enrollment of 12,000 offers the diversity of a large school, while preserving close personal contact between peers and faculty. The University's Maine Center for the Arts, the Hauck Auditorium, and Pavilion Theatre provide many cultural opportunities, in addition to those in the nearby city of Bangor. Less than an hour away from campus are the beautiful Maine Coast and Acadia National park, alpine and cross-country ski resorts, and northern wilderness areas of Baxter State Park and Mount Katahdin.

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Research Areas:
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Artificial Intelligence
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Neural Computation
Polymer Processing
Polymerization Reaction Engineering
Process Control
Separation Processes
Systems Engineering
Turbulence and Mixing

For Applications and Further Information, Write:
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Department of Chemical and Nuclear Engineering
University of Maryland
College Park, Md. 20742
The Chemical Engineering Department at the University of Massachusetts offers graduate programs leading to M.S. and PhD. degrees in Chemical Engineering. Active research areas include polymer engineering, catalysis, design, and basic engineering sciences. Close coordination characterizes research in polymers which can be conducted in either the Chemical Engineering Department or the Polymer Science and Engineering Department. Financial aid, in the form of research assistantships and teaching assistantships, is available. Course of study and area of research are selected in consultation with one or more of the faculty listed below.

For further details, please write to
Prof. Ka M. Ng
Graduate Program Director
Department of Chemical Engineering
University of Massachusetts
Amherst, MA 01003

or

Prof. M. Muthukumar
Graduate Program Director
Dept. of Polymer Science and Engineering
University of Massachusetts
Amherst, MA 01003

*Joint appointments in Chemical Engineering and Polymer Science and Engineering
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◆ RESEARCH AREAS ◆

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Catalysis and Reaction Engineering
Combustion
Computer-Aided Design
Electrochemistry
Energy Conversion
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Kinetics and Reaction Engineering
Microelectronic Materials Processing
Polymers
Process Dynamics and Control
Surfaces and Colloids
Transport Phenomena

MIT also operates the School of Chemical Engineering Practice, with field stations at the General Electric Company in Albany, New York, the Dow Chemical Company in Midland, Michigan, Syntex in Boulder, Colorado, and the Chevron Research Company in Richmond, California.

For more information contact: Chemical Engineering Headquarters, 66-350, Massachusetts Institute of Technology, Cambridge, MA 02139
Phone: (617) 253-4561; FAX: (617) 253-9695
Chemical Engineering at
The University of Michigan

1. H. Scott Fogler, Chairman  Flow in porous media, microelectronics processing
2. Stacy G. Bike  Colloids, transport, electrokinetic phenomena
3. Dale E. Briggs  Coal processes
4. Brice Carnahan  Numerical methods, process simulation
5. Rane L. Curl  Rate processes, mathematical modeling
6. Frank M. Donahue  Electrochemical engineering
7. Erdogan Gulari  Interfacial phenomena, catalysis, surface science
8. Robert H. Kadlec  Ecosystems, process dynamics
9. Costas Kravaris  Non-linear process control, system identification
10. Jennifer J. Linderman  Engineering approaches to cell biology
11. Bernhard O. Palsson  Cellular bioengineering
12. Tasos C. Papanastasiou  Fluid mechanics, rheology, polymers
13. Phillip E. Savage  Reaction pathways in complex systems
14. Johannes Schwank  Heterogeneous catalysis, surface science
15. Levi T. Thompson, Jr.  Catalysis, processing materials in space
17. James O. Wilkes  Numerical methods, polymer processing
18. Gregory S. Y. Yeh  Chain conformation in polymers
19. Robert M. Ziff  Aggregation processes, statistical mechanics

For More Information, Contact:
Prof. B. Carnahan,
Graduate Program Advisor
Department of Chemical Engineering
The University of Michigan
Ann Arbor, MI 48109-2136
313 763-1148
GRADUATE STUDY IN CHEMICAL ENGINEERING AT

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FACULTY AND RESEARCH INTERESTS

D. K. ANDERSON, Chairman
Ph.D., 1960, University of Washington
Transport Phenomena, Diffusion in Polymer Solutions

K. A. BERGLUND
Ph.D., 1981, Iowa State University
Condensation Processes from Solution, Food Engineering, Applications of Laser Spectroscopy, Bioseparations

D. M. BREIDIS
Ph.D., 1981, Iowa State University
Biochemical Engineering, Ceramic Powder Processing

C. M. COOPER, Professor Emeritus
Sc.D., 1949, Massachusetts Institute of Technology
Thermodynamics and Phase Equilibria, Modeling of Transport Processes

L. T. DRZAL
Ph.D., 1974, Case Western Reserve University
Surface and Interfacial Phenomena, Adhesion, Composite Materials, Surface Characterization, Surface Modification of Polymers

H. E. GRETHELEIN
Ph.D., 1962, Princeton University
Biomass Conversion, Bio-Degradation, Waste Treatment, Bio-process Development, Distillation, Biochemical Engineering

E. A. GRULKE
Ph.D., 1975, Ohio State University
Mass Transport Phenomena, Polymer Devolatilization, Biochemical Engineering, Food Engineering

M. C. HAWLEY
Ph.D., 1964, Michigan State University
Kinetics, Catalysis, Reactions in Plasmas, Polymerization Reactions, Composite Processing, Biomass Conversion, Reaction Engineering

K. JAYARAMAN
Ph.D., 1975, Princeton University
Polymer Rheology, Melt Blending of Polymers, Two-Phase Flow in Polymer Processing, Applied Acoustics

C. T. LIRA
Ph.D., 1985, University of Illinois at Urbana-Champaign
Thermodynamics and Phase Equilibria of Complex Systems, Supercritical Fluid Studies

D. J. MILLER
Ph.D., 1982, University of Florida
Kinetics and Catalysis, Reaction Engineering, Carbon Gasification, Catalytic Conversion of Biomass-Derived Compounds

C. A. PETTY
Ph.D., 1970, University of Florida
Fluid Mechanics, Turbulent Transport Phenomena, Solid-Fluid and Liquid-Liquid Separations, Polymer Composite Processing

R. M. WORDEN
Ph.D., 1986, University of Tennessee
Biochemical Engineering, Immobilized Cell Technology, Bioreactor Dynamics and Control

FOR ADDITIONAL INFORMATION WRITE

Coordinator of Graduate Recruiting
Department of Chemical Engineering, A202 Engineering Building
Michigan State University
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- Electrochemical Processes
- Surface Science
- Sols, Gels
- Biomedical Materials

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- Microelectronic Materials
- Preparation Processes
- Suspension Processing
- Ceramic Microstructures

- Physical Metallurgy
- Rheology
- Metal/Semiconductor Interfaces
- Materials Science

- Mechanical Metallurgy
- Diffusion and Kinetics
- Ceramic Microstructures

- Chemical Engineering and Materials Science
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Graduate Admissions
Chemical Engineering and Materials Science
University of Minnesota
421 Washington Ave. S.E.
Minneapolis, MN 55455

For information and application forms, write:
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Chemical Engineering and Materials Science
University of Minnesota
421 Washington Ave. S.E.
Minneapolis, MN 55455
Department of Chemical Engineering

UNIVERSITY OF MISSOURI — ROLLA

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Contact Dr. J. W. Johnson, Chairman
Day Programs M.S. and Ph.D. Degrees

FACULTY AND RESEARCH INTERESTS

N. L. BOOK (Ph.D., Colorado) • Computer aided Process Design, Bioconversion

O. K. CROSSLER (Ph.D., Rice) • Transport Properties, Kinetics, Catalysis

M. E. FINDLEY (Ph.D., Florida) • Biochemical Studies, Biomass Utilization

J. W. JOHNSON (Ph.D. Missouri) • Electrode Reactions, Corrosion

A. I. LIAPIS (Ph.D., ETH-Zurich) • Adsorption, Freeze Drying, Modeling, Optimization, Reactor Design

J. M. D. MAC ELROY (Ph.D., University College Dublin) • Transport Phenomena, Heterogeneous Catalysis, Drying, Statistical Mechanics

D. B. MANLEY (Ph.D., Kansas) • Thermodynamics, Vapor-Liquid Equilibrium

N. C. MOROSOFF (Ph.D., Brooklyn Tech) • Plasma Polymerization, Membranes

P. NEOGI (Ph.D., Carnegie-Mellon) • Interfacial Phenomena

B. E. POLING (Ph.D., Illinois) • Kinetics, Energy Storage, Catalysis

X B REED, JR. (Ph.D., Minnesota) • Fluid Mechanics, Drop Mechanics, Coalescence Phenomena, Liquid-Liquid Extraction, Turbulence Structure

O. C. SITTON (Ph.D., Missouri-Rolla) • Bioengineering

R. C. WAGGONER (Ph.D., Texas A&M) • Multistage Mass Transfer Operations, Distillation, Extraction, Process Control

R. M. YBARRA (Ph.D., Purdue) • Rheology of Polymer Solutions, Chemical Reaction Kinetics

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For admissions information contact:
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Surface science
Aerosol physics
Materials characterization

FACULTY

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D. M. Smith
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F. L. Williams (chairman)

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Albuquerque's southwestern climate and rugged mountainous terrain provide plenty of opportunities for outdoor recreation such as skiing, hiking and whitewater rafting.

For more information write to:
Prof. Abhaya Datye
Department of Chemical and Nuclear Engineering
The University of New Mexico
Albuquerque, NM 87131
FACULTY AND RESEARCH INTERESTS

Ruben Carbonell (Princeton)  
Multi-Phase Transport Phenomena; Bioseparations

Rey Chern (NCSU)  
Structure-Property Relations of Polymers; Membrane Separations

Peter S. Fedkiw (Berkeley)  
Electrochemical Engineering

Richard M. Felder (Princeton)  
Computer-Aided Manufacturing of Specialty Chemicals; Process Simulation and Optimization

James K. Ferrell (NCSU)  
Heat Transfer; Process Control; Coal Gasification

Benny D. Freeman (Berkeley)  
Polymer Physical Chemistry

Christine S. Grant (Georgia Tech)  
Electrokinetic Separations; Surface Science; Particle Technology

Carol K. Hall (Stony Brook)  
Statistical Thermodynamics; Bioseparations; Semiconductor Interfaces

Harold B. Hopfenberg (MIT)  
Transport in Polymers; Controlled Membrane Separations

Peter K. Kilpatrick (Minnesota)  
Interfacial and Surfactant Science; Bioseparations

H. Henry Lamb (Delaware)  
Heterogeneous Catalysis; Surface Science

P. K. Lim (Illinois)  
Interfacial Phenomena; Homogeneous Catalysis; Free Radical Chemistry

David F. Ollis (Stanford)  
Biochemical Engineering; Heterogeneous Photocatalysis

Michael R. Overcash (Minnesota)  
Improving Manufacturing Productivity by Waste Reduction; Environment

Steven W. Peretti (Caltech)  
Genetic and Metabolic Engineering; Microbial, Plant and Animal Cell Culture

George W. Roberts, Head (MIT)  
Heterogeneous Catalysis; Reaction Kinetics; Reactor Engineering: Gas Separations

C. John Setzer, Asst. Head (Ohio State)  
Plant and Process Economics and Management

Edward P. Stahel (Ohio State)  
Chemical and Polymer Reaction Engineering

Vivian T. Stannett (Brooklyn Poly)  
Pure and Applied Polymer Science

Hubert Winston (NCSU)  
Chemical Process Control; Oil Field Reservoir Dynamics

Inquiries to: Prof. Carol K. Hall, Director of Graduate Studies, (919) 737-3571
Chemical Engineering at

Northwestern University

S. George Bankoff
Two-phase heat transfer, fluid mechanics

John B. Butt
Chemical reaction engineering

Stephen H. Carr
Solid state properties of polymers

Buckley Crist, Jr.
Polymer science

Joshua S. Dranoff
Chemical reaction engineering, chromatographic separations

Thomas K. Goldstick
Biomedical engineering, oxygen transport in the human body

Iftekhar Karimi
Computer-aided design, scheduling of noncontinuous processes

Harold H. Kung
Kinetics, heterogeneous catalysis

Richard S. H. Mah
Computer-aided process planning, design and analysis

William M. Miller
Biochemical engineering

E. Terry Papoutsakis
Biochemical engineering

Mark A. Petrich
Electronic materials, applications of solid state NMR

Gregory Ryskin
Fluid mechanics, computational methods, polymeric liquids

Wolfgang M. H. Sachtler
Heterogeneous catalysis

John M. Torkelson
Polymer science

M. Grae Worster
Fluid mechanics, convective heat and mass transfer

For information and application to the graduate program, write

John M. Torkelson
Director of Graduate Admissions
Department of Chemical Engineering
Northwestern University
Evanston, Illinois 60208
The University of Notre Dame offers programs of graduate study leading to the Master of Science and Doctor of Philosophy degrees in Chemical Engineering. The requirements for the master's degree are normally completed in twelve to fourteen months. The doctoral program requires about four years of full-time study beyond the bachelor's degree. These programs can usually be tailored to accommodate students whose undergraduate degrees are in areas of science or engineering other than chemical engineering.

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For further information, write to:

Dr. M. J. McCready
Department of Chemical Engineering
University of Notre Dame
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- Robert S. Brodkey, Wisconsin 1952, Turbulence, Mixing, Image Analysis, Reactor Design, and Rheology
- Jeffery J. Chalmers, Cornell 1988, Biochemical Engineering, Protein Excretion and Production, and Immobilized Cell Reactor Design
- L.S. Fan, West Virginia 1975, Fluidization, Chemical & Biochemical Reaction Engineering, and Mathematical Modeling
- Morton H. Friedman, Michigan 1961, Biomedical Engineering, and Hemodynamics
- Edwin R. Haering, Ohio State 1966, Reaction Engineering, Catalysis, and Adsorption
- Harry C. Hershey, Missouri-Rolla 1965, Thermodynamics, and Drag Reduction
- L. James Lee, Minnesota 1979, Polymer Processing, Polymerization, and Rheology
- Umit Ozkan, Iowa State 1984, Heterogeneous Catalysis, and Reaction Kinetics
- Duane R. Skidmore, Fordham 1960, Coal Processing, and Biochemical Engineering
- Thomas L. Sweeney, Case 1962, Air Pollution Control, Heat Transfer, and Legal Aspects of Engineering
- Shang-Tian Yang, Purdue 1984, Biochemical Engineering and Biotechnology, Fermentation Processes, and Kinetics
- Jacques L. Zakin, New York 1959, Drag Reduction, Rheology, and Emulsions

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Ohio University

Chemical Engineering

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Financial Aid
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Ohio University is an affirmative action institution.

Research Areas
- Coal Utilization Technologies
- Polymerization Reaction Engineering
- Fine Particle Technology
- Separation Processes
- Process Control and Simulation
- Corrosion
- Environmental Assessment

For further information:
Director of Graduate Studies, Department of Chemical Engineering, 172 Stocker Center, Ohio University, Athens, Ohio 45701-2979
Areas Of Research Interest:

- SURFACTANTS
- CORROSION
- THERMODYNAMICS
- BIOCHEMICAL AND BIOMEDICAL ENGINEERING
- STATISTICAL MECHANICS
- SYNTHETIC FUELS
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Graduate Program Coordinator
School of Chemical Engineering and Materials Science
University of Oklahoma
100 East Boyd
Norman, Oklahoma 73019
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Catalysis        Heat Transfer    Ion Exchange
Design           Equations of State Kinetics
Equations of State

M.M. Johnson    W.E. Payne    R.L. Robinson, Jr.    M. Seapan    J. Wagner

Fluid Flow       Gas Processing   Hazardous Wastes
Ground Water Quality Heat Transfer   Ion Exchange
Kinetics

Address inquiries to:
Robert L. Robinson, Jr.
School of Chemical Engineering
Oklahoma State University
Stillwater, OK 74078-0537
University of Pennsylvania Chemical Engineering

Stuart W. Churchill
Combustion, thermoacoustic convection, rate processes

Gregory C. Farrington
Electrochemistry, solid state and polymer chemistry, catalysis

William C. Forsman
Polymer science and engineering, graphite intercalation

Eduardo D. Glandt
Classical and statistical thermodynamics, random media

Raymond J. Gorte
Heterogeneous catalysis, surface science, zeolites

David J. Graves
Biochemical and biomedical engineering, bioseparations

Douglas A. Lauffenburger
Biomedical/biochemical engineering, mathematical modeling

Mitchell Litt
Biorheology, transport systems, biomedical engineering

Alan L. Myers
Adsorption of gases and liquids, thermodynamics of electrolytes

Daniel D. Perlmutter
Chemical reactor design, superconducting composites

John A. Quinn
Membrane transport, biochemical/biomedical engineering

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

Lyle H. Ungar
Crystal growth, artificial intelligence in process control

T. Kyle Vanderlick
Thin-film and interfacial phenomena

John M. Vohs
Metal oxide surface chemistry

Paul B. Weisz
Molecular selectivity in chemical and life processes

Pennsylvania's chemical engineering program is designed to be flexible while emphasizing the fundamental nature of chemical and physical processes. Students may focus their studies in any of the research areas of the department. The full resources of this Ivy League university, including the Wharton School of Business and one of this country's foremost medical centers, are available to students in the program. The cultural advantages, historical assets, and recreational facilities of a great city are within walking distance of the University.

For additional information, write:

Director of Graduate Admissions
Department of Chemical Engineering
311A Towne Building
University of Pennsylvania
Philadelphia, Pennsylvania 19104-6393
For application forms and further information, write to
Chairman, Graduate Admissions Committee
Department of Chemical Engineering
158 Fenske Laboratory
The Pennsylvania State University
University Park, PA 16802

Individuals holding the B.S. in Chemistry or other related areas are encouraged to apply.
University of Pittsburgh

GRADUATE PROGRAMS
MS in Chemical Engineering
MS in Petroleum Engineering
Dual MS in Chemical/Petroleum Engineering
PhD in Chemical Engineering

RESEARCH AREAS
Catalysis
Bioengineering
Surface Chemistry
Reactor Engineering
Interphase Transport
Particulate Systems
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Supercritical Extractions
Gas Hydrates
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Secondary Oil Recovery

FACULTY
Mohammed M. Ataai
Eric J. Beckman
Donna G. Blackmond
Alan J. Brainard
Shiao-Hung Chiang
James T. Cobb, Jr.
Robert M. Enick
James G. Goodwin, Jr.
Gerald D. Holder
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George Marcelin
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Irving Wender

FOR MORE INFORMATION
Graduate Coordinator
Chemical/Petroleum Engineering
University of Pittsburgh
School of Engineering
Pittsburgh, PA 15261

SCHOOL OF ENGINEERING
RESEARCH AREAS

Composite Materials
Computer Aided Process Design
Engineering Properties of Polymers
Fluid Mechanics
Heat and Mass Transfer
Plasma and Thin Films
Polymer Processing
Polymer Morphology
Polymer Synthesis and Modification
Rheology
Separation Sciences
Thermodynamic Properties of Fluids

Programs lead to Master of Science and Ph.D. degrees.
Fellowships and research assistantships are available.

For further information, please contact:
Professor A.S. Myerson
Head, Department of Chemical Engineering
Polytechnic University
333 Jay Street
Brooklyn, NY 11201

Polytechnic University is the nation's second oldest technological university. A private, coeducational university founded in 1854, it was known as Brooklyn Poly until 1973 when it merged with New York University's School of Engineering and Science to create Polytechnic Institute of New York. In 1985, its name was changed to Polytechnic University reflecting its position as one of the major technological universities in the New York metropolitan region.
GRADUATE STUDIES
IN
Chemical Engineering

Research Areas
- Applied Mathematics
- Artificial Intelligence
- Biochemical Engineering
- Biomedical Engineering
- Catalysis and Reaction Engineering
- Colloids and Interfacial Engineering
- Operations and Design
- Environmental Science
- Materials and Microelectronics Processing
- Parallel Computing and Combinatorics
- Polymer Science and Engineering
- Process Systems Engineering
- Separation Processes
- Surface Science and Engineering
- Thermodynamics and Statistical Mechanics
- Transport Phenomena

Contact Us Today
Graduate Information
School of Chemical Engineering
Purdue University
West Lafayette, IN 47907

Faculty
L.F. Albright  J.F. Pekny
R.P. Andres  N.A. Peppas
J.M. Caruthers  D. Ramkrishna
K.C. Chao  G.V. Reklaitis
W.N. Delgass  J.H. Seo
R.E. Eckert  R.G. Squires
A.H. Emery  C.G. Takoudis
E.I. Franses  J. Talbot
R.A. Greenkorn  G.T. Tsao
R.E. Hannemann  V. Venkatasubramanian
R.N. Houze  N.H.L. Wang
D.P. Kessler  P.C. Wankat
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D. D. DO (Queensland)
P. F. GREENFIELD (N.S.W.)
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G. W. PACE (MIT)
D. H. RANDERSON (N.S.W.)

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- Crystallization • Polymer Processing • Rheology • Chemical Reactor Analysis • Energy Resource Studies
- Oil Shale Processing • Water and Wastewater Treatment • Environmental Systems Modeling
- Particle Mechanics • Process Simulation • Fermentation Systems • Tissue Culture • Enzyme Engineering • Environmental Control • Process Economics • Mineral Processing • Adsorption • Membrane Processes • Hybridoma Technology • Numerical Analysis • Large Scale Chromatography

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The Department occupies its own building, is well supported by research grants, and maintains an extensive range of research equipment. It has an active postgraduate programme, which involves course work and research work leading to M. Eng. Studies, M. Eng. Science, M. Sci. Studies, M. Agr. Studies, and Ph.D. degrees.

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The University is one of the largest in Australia, with more than 18,000 students. Brisbane, with a population of about one million, enjoys a pleasant climate and attractive coasts which extend northward into the Great Barrier Reef.

For further information write to: Co-ordinator of Graduate Studies, Department of Chemical Engineering, University of Queensland, St. Lucia, Qld. 4067, AUSTRALIA
Ph.D. and M.S. Programs in Chemical Engineering

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- Air pollution control
- Biochemical engineering
- Bioseparations
- Fluid-particle systems
- Heat transfer
- High temperature kinetics
- Interfacial phenomena
- Microelectronics manufacturing
- Multiphase flow
- Polymer reaction engineering
- Process control and design
- Separation engineering
- Simultaneous diffusion and chemical reaction
- Thermodynamics
- Transport Processes

For full details write
Dr. P.K. Lashmet, Executive Officer
Department of Chemical Engineering
Rensselaer Polytechnic Institute,
Troy, New York 12180-3590

The Faculty

Michael M. Abbott  Ph.D., Rensselaer
Elmar R. Altwicker  Ph.D., Ohio State
Georges Belfort  Ph.D., California—Irvine
B. Wayne Bequette  Ph.D., Texas—Austin
Henry R. Bungay III  Ph.D., Syracuse
Chan I. Chung  Ph.D., Rutgers
Steven M. Cramer  Ph.D., Yale
Arthur Fontijn  D.Sc., Amsterdam
William N. Gill  Ph.D., Syracuse
Richard T. Lahey, Jr.  Ph.D., Stanford
Peter K. Lashmet  Ph.D., Delaware
Howard Littman  Ph.D., Yale
Morris H. Morgan III  Ph.D., Rensselaer
Charles Muckenfuss  Ph.D., Wisconsin
E. Bruce Nauman  Ph.D., Leeds
Joel L. Plawsky  D.Sc., M.I.T.
Sanford S. Sternstein  Ph.D., Rensselaer
Hendrick C. Van Ness  D.Eng., Yale
Peter C. Wayner, Jr.  Ph.D., Northwestern
Robert H. Wentorf, Jr.  Ph.D., Wisconsin
Rice University
Graduate Study in Chemical Engineering

APPLICATIONS AND INQUIRIES
Chairman, Graduate Committee
Department of Chemical Engineering
PO Box 1892
Rice University
Houston, TX 77251

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FACULTY
- William W. Akers (Michigan, 1950)
- Constantine D. Armeniades (Case Western Reserve, 1969)
- Sam H. Davis, Jr. (MIT, 1957)
- Derek C. Dyson (London, 1966)
- Michael W. Glacken (MIT, 1987)
- J. David Hellums (Michigan, 1961)
- Joe W. Hightower (Johns Hopkins, 1963)
- Riki Kobayashi (Michigan, 1951)
- Larry V. McIntire (Princeton, 1970)
- Clarence A. Miller (Minnesota, 1969)
- Mark A. Robert (Swiss Fed. Inst. of Technology, 1980)
- Ka-Yiu San (CalTech, 1984)
- Jacqueline Shanks (CalTech, 1989)
- Kyriacos Zygourakis (Minnesota, 1981)

RESEARCH INTERESTS
- Applied Mathematics
- Biochemical Engineering
- Biomedical Engineering
- Equilibrium Thermodynamic Properties
- Fluid Mechanics
- Interfacial Phenomena
- Kinetics and Catalysis
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Department of Chemical Engineering
University of Rochester
Rochester, New York 14627
Phone: (716) 275-4042

Faculty and Research Areas

S. H. CHEN, Ph.D. 1981, Minnesota
Polymer Science and Engineering, Transport Phenomena, Optical Materials

E. H. CHIMOWITZ, Ph.D. 1982, Connecticut
Computer-Aided Design, Super-Critical Extraction, Control

M. R. FEINBERG, Ph.D. 1968, Princeton
Complex Reaction Systems, Applied Mathematics

J. R. FERRON, Ph.D. 1958, Wisconsin
Molecular Transport Processes, Applied Mathematics

J. C. FRIEDLY, Ph.D. 1965, California (Berkeley)
Process Dynamics, Control, Heat Transfer

R. H. HEIST, Ph.D. 1972, Purdue
Nucleation, Solid State, Ultrafine Particles

S. A. JENKHE, Ph.D. 1985, Minnesota
Polymer Science and Engineering, Electronic and Optical Materials, Chemical Sensors

J. JORNE, Ph.D. 1972, California (Berkeley)
Electrochemical Engineering, Microelectronic Processing, Theoretical Biology

R. H. NOTTER, Ph.D. 1969, Washington (Seattle)
M.D. 1980, Rochester
Biomedical Engineering, Lung Disease and Toxicology, Aerosols

H. J. PALMER, Ph.D. 1971, Washington (Seattle)
Interfacial Phenomena, Mass Transfer, Bioengineering

H. SALTSBURG, Ph.D. 1955, Boston
Surface Phenomena, Catalysis, Molecular Scattering

S. V. SOTIRCHOS, Ph.D. 1982, Houston
Reaction Engineering, Combustion and Gasification of Coal, Gas-Solid Reactions

J. H. D. WU, Ph.D. 1987, M.I.T.
Biochemical Engineering, Fermentation, Biocatalysis, and Industrial Microbiology
M.S. and Ph.D. Programs
In the Department of Chemical and Biochemical Engineering

Areas of Teaching and Research

Chemical Engineering Fundamentals
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Director of Graduate Program
Dept. of Chemical and Biochemical Engineering
Rutgers, The State University of New Jersey
P.O. Box 909
Piscataway, NJ 08855-0909

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Faculty

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J. A. Biesenberger (PhD, Princeton U.)
G. B. Delancey (PhD, Pittsburgh U.)
C. G. Gogos (PhD, Princeton U.)
R. Griskey (PhD, Carnegie Inst. Tech.)
D. M. Kalyon (PhD, McGill U.)
S. Kovenklioglu (PhD, Stevens)
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Department of Chemistry and Chemical Engineering
Stevens Institute of Technology
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201-420-5546

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Cynthia S. Hirtzel
George C. Martin
Philip A. Rice (chairman)
Ashok S. Sangani
Klaus Schroder
James A. Schwarz
S. Alexander Stern
Lawrence L. Tavlarides
Chi Tien

for information:

Dr. George C. Martin
Dept. of Chemical Engineering and Materials Science
320 Hinds Hall
Syracuse University
Syracuse, NY 13244
(315) 443-2559

Kleine Welten (Small Worlds) VII, Wassily Kandinsky, c. 1922, Syracuse University Art Collection

Syracuse University
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- Bioprocess Research Facility at ORNL

PROCESS CONTROL
- Measurement and Control Engineering Center

POLYMER PROCESSING
- Center for Materials Processing

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P.R. Bienkowski  Bioprocessing, Thermodynamics
D.C. Bogue  Polymers, Rheology
D.D. Bruns  Process Control, Modeling
C.H. Byers¹  Separations & Transport
E.S. Clark  Polymers
H.D. Cochran¹  Thermodynamics
R.M. Counce  Separations & Transport
B.H. Davison¹  Bioprocessing
T.L. Donaldson¹  Bioprocessing
J.F. Fellers  Polymers
G.C. Frazier  Bioprocessing, Kinetics

M.G. Hansen  Rheology, Polymers and Composites
H.W. Hsu  Bioprocessing, Transport
C.F. Moore  Process Control
J.J. Perona (Head)  Separations & Transport
C.D. Scott¹  Bioprocessing, Separations
T.C. Scott¹  Bioprocessing, Separations
C.O. Thomas  Computer-aided Design, Economics
T.W. Wang  Process Control, Bioprocessing
J.S. Watson¹  Separations & Transport, Nuclear Fusion
F.E. Weber  Computer-aided Design, Radiation Chemistry

¹ Adjunct Faculty at Oak Ridge National Laboratory (ORNL), 20 miles from the main campus at Knoxville

WRITE TO:
DEPARTMENT OF CHEMICAL ENGINEERING
UNIVERSITY OF TENNESSEE
KNOXVILLE, TN 37996-2200
Faculty and Research Interests

R. W. Flumerfelt, Head, Ph.D., Northwestern, 1965
- fluid mechanics, interfacial phenomena

A. Akgerman, Ph.D., Virginia, 1971
- reaction engineering, waste treatment

R. G. Anthony, Ph.D., Texas, 1966
- catalysis, reaction engineering

A. J. Appleby, Ph.D., Cambridge (UK), 1965
- electrochemistry

D. B. Bukur, Ph.D., Minnesota, 1974
- reaction engineering, math methods

J.A. Bullin, Ph.D., Houston, 1972
- gas sweetening, asphalt characterization

B. E. Dale, Ph.D., Purdue, 1979
- biochemical engineering

R. Darby, Ph.D., Rice, 1962
- rheology, ploymers

R. R. Davison, Ph.D., Texas A&M, 1962
- methanol fuel, asphalt characterization

L. D. Durbin, Ph.D., Rice, 1961
- process control

P. T. Eubank, Ph.D., Northwestern, 1961
- thermodynamics

A. M. Gadalla, Ph.D., Shefield (UK), 1964
- ceramics, materials science

C. J. Glover, Ph.D., Rice, 1974
- polymer solutions

K. R. Hall, Ph.D., Oklahoma, 1967
- thermodynamics

D. T. Hanson, Ph.D., Minnesota, 1968
- biochemical engineering

C. D. Holland, Ph.D., Texas A&M, 1963
- separation processes, distillation, unsteady-state processes

J. C. Holste, Ph.D., Iowa State, 1973
- thermodynamics

M.T. Holtzapple, Ph.D., Pennsylvania, 1978
- biochemical engineering

T.R. Irvin, Ph.D., MIT, 1983
- toxicology

M. Nikolao, Ph.D., University of California, Los Angeles, 1989
- process control, optimization and design

H.J. Ploehn, Ph.D., Princeton, 1988
- colloidal and interfacial systems

J.C. Slattery, Ph.D., University of Wisconsin, 1959
- polymers, transport phenomena

A.T. Watson, Ph.D., Cal. Tech., 1979
- porous media, math modeling

R.E. White, Ph.D., University of California, Berkeley, 1977
- electrochemistry

For Additional Information
Graduate Admissions Office
Department of Chemical Engineering
Texas A&M University
College Station, Texas 77843-3122
(409) 845-3361

Texas A&M University

The Department of Chemical Engineering at Texas A&M University has an enrollment of about 110 graduate students. Qualified master's students receive a 12-month stipend. These range from $950 to $1100 for Ph.D. candidates. Additional special awards of $250 per month are available for outstanding Ph.D. students. Out-of-state students who receive stipends are exempt from nonresident tuition and pay the same tuition and fees (currently about $500 per semester) as Texas residents.

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Admission to Texas A&M University and any of its sponsored programs is open to qualified individuals regardless of race, color, age, religion, sex, national origin or educationally unrelated handicaps.
## Chemical Engineering at Texas

### Research Interests

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<th>Joel W. Barlow</th>
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<td>Deposition</td>
<td>Adam Heller</td>
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<td>Hugo Steinrümper</td>
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<td>Isaac Trachtenberg</td>
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<td>Louisiana State</td>
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</tbody>
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### Faculty

- Joel W. Barlow, Wisconsin
- James R. Brock, Wisconsin
- Thomas F. Edgar, Princeton
- John G. Ekerdt, Berkeley
- James R. Fair, Texas
- George Georgiou, Cornell
- Adam Heller, Hebrew (Jerusalem)
- David M. Himmelblau, Washington
- Jeffrey A. Hubbell, Rice
- Keith P. Johnston, Illinois
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<table>
<thead>
<tr>
<th>Name</th>
<th>Research Interests</th>
</tr>
</thead>
<tbody>
<tr>
<td>R. Byron Bird</td>
<td>Transport phenomena, polymer fluid dynamics, polymer kinetic theory</td>
</tr>
<tr>
<td>Douglas C. Cameron</td>
<td>Biochemical engineering</td>
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<tr>
<td>Thomas W. Chapman</td>
<td>Electrochemistry, multiphase reactors, hydrometallurgy</td>
</tr>
<tr>
<td>Camden A. Coberly</td>
<td>Hazardous waste management, process design, composite materials processing</td>
</tr>
<tr>
<td>Stuart L. Cooper</td>
<td>Polymer structure-property relations, biomaterials</td>
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<tr>
<td>E. Johansen Crosby</td>
<td>Spray and suspended particle processing</td>
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<td>James A. Dumesic</td>
<td>Kinetics and catalysis, surface chemistry</td>
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<td>Charles G. Hill, Jr.</td>
<td>kinetics and catalysis, membrane separation processes</td>
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<td>Sangtae Kim</td>
<td>Fluid mechanics, applied mathematics</td>
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<td>James A. Koutsky</td>
<td>Polymer science, adhesives composites</td>
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<td>Kinetics, catalysis, electrochemistry, chromatography, hydrometallurgy</td>
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<td>W. Harmon Rey</td>
<td>Process dynamics and control, reaction engineering, polymerization</td>
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<td>Thatcher W. Root</td>
<td>Surface chemistry, catalysis</td>
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<td>Dale F. Rudd</td>
<td>Process design and industrial development</td>
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<td>Glenn A. Sather</td>
<td>Development of instructional program</td>
</tr>
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<td>Warren E. Stewart</td>
<td>Reactor modeling, transport phenomena, applied mathematics</td>
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<td>Ross E. Swaney</td>
<td>Process synthesis and optimization, computer-aided design</td>
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J. F. MacGregor, Ph.D. (Wisconsin)  
Computer Process Control, Polymer Reaction Engineering

T. E. Martin, Ph.D. (Massachusetts)  
Computer Process Control

R. H. Pelton, Ph.D. (Bristol)  
Water Soluble Polymers, Colloid Polymer Systems

L. W. Shemilt, Ph.D. (Toronto)  
Electrochemical Mass Transfer, Corrosion, Thermodynamics

P. A. Taylor, Ph.D. (Wales)  
Computer Process Control

M. Tsezos, Ph.D. (McGill)  
Wastewater Treatment, Biosorptive Recovery

J. Vlachopoulos, D.Sc. (Washington University)  
Polymer Processing, Rheology, Numerical Methods

P. E. Wood, Ph.D. (Caltech)  
Turbulence Modeling, Mixing

D. R. Woods, Ph.D. (Wisconsin)  
Surface Phenomena, Cost Estimation, Problem Solving

J. D. Wright, Ph.D. (Cambridge)/Part Time  
Computer Process Control, Process Dynamics and Modeling

M. En., and Ph.D. Programs
Research Scholarships and Teaching Assistantships are available

For further information, please contact
Professor A. N. Hrymak  
Department of Chemical Engineering  
McMaster University  
Hamilton, Ontario, Canada L8S 4L7

MICHIGAN TECHNOLOGICAL UNIVERSITY

Department of Chemistry and Chemical Engineering

PROGRAM OF STUDY: The department offers a broad range of traditional and interdisciplinary programs leading to the M.S. and Ph.D. degrees. Program areas include the traditional areas of chemistry and chemical engineering with particular emphasis in polymer and composite materials; process design, control, and improvement; free radical chemistry; bioorganic chemistry; and surface Raman spectroscopy.

COST OF TUITION: Full-time in-state graduate tuition is $695/quarter. Tuition is normally included as part of the student's financial support.

THE COMMUNITY: MTU is located in Houghton on the beautiful Keweenaw Peninsula overlooking Lake Superior. The region surrounding MTU is a virtual wilderness of interconnected lakes, rivers, and forest lands. Outdoor activities abound all year with superb fishing, boating, hiking, camping, and skiing available within minutes of campus.

FINANCIAL AID: Financial support in the form of fellowships, research assistantships, and graduate teaching assistantships is available. Starting stipends are $6600 per academic year in addition to tuition.

For more information write:  
Graduate Studies Chairman  
Department of Chemistry and Chemical Engineering  
Michigan Technological University  
Houghton, Michigan 49931

Michigan Technological University is an equal opportunity educational institution/equal opportunity employer.
MONASH UNIVERSITY
Melbourne, Australia
Department of Chemical Engineering, including the Australian Pulp and Paper Institute


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  • J. R. G. ANDREWS
  • D. J. BRENNAN
  • H. T. CULLINAN
  • G. A. HOLDER
  • D. F. A. KOCH
  • J. F. MATHEWS
  • W. E. OLBRICH
  • I. G. PRINCE
  • O. E. POTTER
  • T. SRIDHAR
  • C. TIU
  • P. H. T. UHLHERR
  • M. R. W. WALMSLEY

• RESEARCH AREAS •
  • Gas-Solid Fluidisation
  • Brown Coal - Hydroliquefaction, Gasification, Oxygen Removal, Fluidised Bed Drying
  • Pulp and Paper Technology
  • Chemical Reaction Engineering - Gas-Liquid, Gas-Solid, Three Phase
  • Heterogeneous Catalysis - Catalyst Design
  • Transport Phenomena - Heat and Mass Transfer, Transport Properties
  • Extractive Metallurgy and Mineral Processing
  • Rheology - Suspensions, Polymers, Foods
  • Biochemical Engineering - Continuous Culture
  • Waste Treatment and Water Purification
  • Process Economics

FOR FURTHER INFORMATION AND APPLICATION WRITE:
Graduate Studies Coordinator
Department of Chemical Engineering
Monash University
Clayton, Victoria, 3168, Australia

Montana State University

Montana State offers M.S. and Ph.D. degree programs in chemical engineering with research programs in Separations, Biotechnology, Catalysis, and Materials Science. Interdisciplinary research opportunities exist with the University's Institute for Chemical and Biological Process Analysis (IPA) and the new Center for the Synthesis and Characterization of Advanced Materials (SACAM).

Faculty

• L. BERG (Ph.D., Purdue) - Extractive Distillation
• W. G. CHARACKLIS, Adjunct, Director IPA (Ph.D., Johns Hopkins) - Microbial Engineering, Industrial Water Quality
• M. C. DEIBERT (Sc.D., MIT) - Surface Science, Catalysis, Materials - Intermetallic Compounds
• R. W. LARSEN (Ph.D., Penn State) - Biological Processes and Separations
• J. F. MANDELL (Ph.D., MIT) - Composites, Interfaces, Ceramics, Polymers
• F. P. McCANDLESS (Ph.D., MSU) - Membranes, Extractive Crystallization
• R. L. NICKELSON (Ph.D., Minnesota) - Process Control
• T. SAHIN (Ph.D., MSU) - Catalysis, Kinetics, Surface Science, Microelectronics - Chemical Vapor Deposition
• W. P. SCARRAH (Ph.D., MSU) - Supercritical Fluid Extraction, Biomass Energy Conversion
• J. T. SEARS Head (Ph.D., Princeton) - Catalysis, Adsorption of Bacteria on Metals
• D. L. SHAFER (Ph.D., Penn State) - Biomass Energy Conversion, Polymeric Materials, Reactor Engineering

Information

Dr. J. T. Sears, Head, Department of Chemical Engineering
Montana State University, Bozeman, MT 59717
UNIVERSITY OF NEBRASKA

CHEMICAL ENGINEERING

OFFERING GRADUATE STUDY FOR M.S. OR PH.D. WITH RESEARCH IN

- Bio-mass Conversion
- Reaction and Fermentation Kinetics
- Real-time Computing
- Computer-aided Process Design and Process Synthesis
- Polymer Engineering
- Separation Processes
- Surface Science
- Thermodynamics and Phase Equilibria
- Electrochemical and Corrosion Engineering

For Application and Information:
Chairman of Chemical Engineering
236 Avery Hall, University of Nebraska
Lincoln, Nebraska 68588-0126

Graduate study in chemical engineering M.S. and Ph.D. Degrees

Major energy research center:

- Bioengineering
- Food Processing
- Waste Management

- Computer Aided Design
- Oil Recovery
- Chemical Safety

Financial assistance is available.
Special programs for students with B.S. degrees in other fields.

FOR APPLICATIONS AND INFORMATION:

Dr. Ron Bhada, Head
Department of Chemical Engineering
P.O. Box 30001, Dept. 3805
New Mexico State University
Las Cruces, New Mexico 88003-0001

New Mexico State University is an Equal Opportunity Affirmative Action Employer.
THE UNIVERSITY OF NEW SOUTH WALES
SYDNEY, AUSTRALIA

POSTGRADUATE STUDY IN CHEMICAL ENGINEERING AND INDUSTRIAL CHEMISTRY

- RESEARCH AREAS -

Air and Water Pollution Control
Battery Research and Development
Catalysis and Reactor Design
Characterisation and Optimization in Minerals Processing
Chemical Separations
Computational Fluid Mechanics and Rheology
Computer Aided Design and Process Synthesis for Energy Conservation
Corrosion
Electrochemistry
Extractive Metallurgy
Flow Phenomena in Mass Transfer Equipment
Fuel Technology
Glass Technology
High Temperature Materials
Membrane Technology
Particle Technology
Petroleum Engineering
Polymer Science and Engineering
Process Control and Microprocessor Applications
Pyrometallurgical Reactor Modelling
Solvent Extraction
Spontaneous Ignition Phenomena
Supercritical Fluids
Two-Phase Flow
Waste Processing

- THE DEPARTMENT -

This is the largest Chemical Engineering School in Australia, with 25 academic staff, over 400 undergraduates and about 80 postgraduates. The School is well supplied with equipment and is supported by research grants from Government and Industry. The five main departments of Chemical Engineering, Industrial Chemistry, Petroleum Engineering, Fuel Technology and Polymer Science offer course work and research work leading to M.Sc., M.E. and Ph.D. degrees. The breadth and depth of experience available leads to the production of well rounded graduates with excellent job potential. International recognition is only one of the many benefits of a degree from UNSW.

THE UNIVERSITY -

The University is the largest in Australia and is located between the centre of Sydney and the beaches. The cosmopolitan city and the wide range of outdoor activities make life very pleasant for students, and people from America, Europe, Africa and the East feel welcome from their first arrival. For further information concerning specific research areas, facilities, and financial conditions, write to:

Professor A. G. Fane
School of Chemical Engineering & Industrial Chemistry
University of New South Wales
PO Box 1, Kensington, NSW 2033 Australia

COMING TO BOSTON

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- Home of the Red Sox, Celtics, Bruins, Patriots, Marathon
- Nearby ocean beaches, skiing, state parks, Fanuel Hall Marketplace

Major Areas of Research:
- Biotechnology
  - Biopolymers
  - Bioconversion
  - Bioinstrumentation
- Catalysis
- Process Control
- Applied Mathematics
- Process Design
- Heat Transfer

For Information, write:
Ralph A. Buonoane, Ph.D., Chairman
Department of Chemical Engineering
Northeastern University
342 SN-C2E
Boston, MA 02115

Graduate Studies in Chemical Engineering
NORTHEASTERN UNIVERSITY
OREGON STATE UNIVERSITY
Chemical Engineering
M.S. and Ph.D. Programs

FACULTY

S. Kimura  • Reaction Engineering, High-
            Temperature Materials
O. Levenspiel • Reactor Design, Fluidization
K. L. Leven • Process Simulation and Control
R. V. Mrazek • Thermodynamics, Applied
               Mathematics
G. L. Rorrer • Biochemical Reaction Engineering
R. Sproull • Biomass Conversion, Plant Design
J. D. Way • Membrane-Based Separation
            Processes

Our current programs reflect not only traditional chemical engineering fields but also new
technologies important to the Northwest's industries, such as electronic device manufacturing,
forest products, food science and ocean products. Oregon State is located only a short drive from
the Pacific Ocean, white-water rivers and hiking/skiing/climbing in the Cascade Mountains.

For further information, write:
Chemical Engineering Department
Gleeson Hall, Room 103
Oregon State University
Corvallis, Oregon 97331-2702

Princeton University
M.S.E. AND Ph.D. PROGRAMS IN CHEMICAL ENGINEERING

RESEARCH AREAS
Bioengineering; Catalysis; Chemical Reactor/Reaction Engineering; Plasma Processing; Colloidal
Phenomena; Computer Aided Design; Nonlinear Dynamics; Polymer Science; Process Control;
Flow of Granular Media; Rheology; Statistical Mechanics; Surface Science; Thermodynamics and
Phase Equilibria

FACULTY
Jay B. Benziger, Joseph L. Cecchi, Pablo G. Debenedetti, Christodoulos A. Floudas, John K.
Gillham, William W. Graessley, Roy Jackson, Steven F. Karel, Yannis G. Kevrekidis, Morton D.
Kostin, Robert K. Prud'homme, Ludwig Rebenfeld, William B. Russel, Chairman, Dudley A.
Saville, Sankaran Sundaresan

Write to:  Director of Graduate Studies
Chemical Engineering
Princeton University
Princeton, New Jersey 08544

Inquiries can be addressed via Electronic Mail over BITNET to CHEGRAD@PUCC

FALL 1989
Graduate Studies in Chemical Engineering
MSc and PhD Degree Programs

J. Abbot  PhD (McGill)
D.W. Bacon  PhD (Wisconsin)
H.A. Becker  ScD (MIT)
D.H. Bone  PhD (London)
S.H. Cho  PhD (Princeton)
R.H. Clark  PhD (Imperial College)
R.K. Code  PhD (Cornell)
A.J. Daugulis  PhD (Queen's)
J. Downie  PhD (Toronto)
M.F.A. Goosen  PhD (Toronto)
E.W. Grandmaison  PhD (Queen's)
T.J. Harris  PhD (McMaster)
C.C. Hsu  PhD (Texas)
B.W. Wojciechowski  PhD (Ottawa)

- Catalysis & Reaction
  - catalyst aging & decay
  - catalytic oxidation & cracking
  - gas adsorption on catalysis
  - reaction network analysis

- Physical Processing
  - dryforming technology
  - drying of cereal grains
  - turbulent mixing & flow

- Bioreaction & Processing
  - bioreactor modeling and design
  - extractive fermentation
  - fermentation using genetically engineered organisms
  - controlled release delivery systems
  - microencapsulation technology

- Polymer Engineering
  - Ziegler-Natta polymerization
  - reactor analysis, design and control

- Fuels and Energy
  - Fischer-Tropsch synthesis
  - fluidized bed combustion
  - fuel alcohol production
  - gas flames & furnaces
  - heat transfer in steel reheating

- Process Control & Simulation
  - batch reactor control
  - multivariable control systems
  - nonlinear control systems
  - on-line optimization
  - statistical identification of process dynamics

WRITE:
Dr. James C. C. Hsu
Department of Chemical Engineering
Queen's University
Kingston, Ontario, Canada K7L 3N6

UNIVERSITY OF RHODE ISLAND

GRADUATE STUDY IN CHEMICAL ENGINEERING

M.S. and Ph.D. Degrees

CURRENT AREAS OF INTEREST

- Biochemical Engineering
- Corrosion
- Crystallization Processes
- Energy Engineering

- Food Engineering
- Heat and Mass Transfer
- Metallurgy and Ceramics
- Mixing

- Multiphase Flow
- Phase Change Kinetics
- Separation Processes
- Surface Phenomena

APPLICATIONS
APPLY TO: Chairman, Graduate Committee
Department of Chemical Engineering
University of Rhode Island
Kingston, RI 02881

Applications for financial aid should be received not later than Feb. 16
Research Areas

- Kinetics and Catalysis
- Process Control
- Polymers
- Thermodynamics
- Transport Phenomena
- Biotechnology

Faculty

- C. F. Abegg, Ph.D., Iowa State
- R. S. Artigue, D. E., Tulane
- W. W. Bowden, Ph.D., Purdue
- J. A. Caskey, Ph.D., Clemson
- S. C. Hite, Ph.D., Purdue
- S. Leipziger, Ph.D., I.I.T.
- N. E. Moore, Ph.D., Purdue

For Information Write:
Dr. Stuart Leipziger
Dept. Graduate Advisor
Rose-Hulman Institute of Technology
Terre Haute, IN 47803-3999

DEPARTMENT OF CHEMICAL ENGINEERING

Graduate Studies

DEPARTMENT OF CHEMICAL ENGINEERING
University of Saskatchewan

FACULTY AND RESEARCH INTERESTS

N.N. Bakhshi  Fischer Tropsch Reaction Studies, Catalytic Upgrading of Biomass-Derived Oils/Plant Oils, Biomass Pyrolysis, Heavy Oil Upgrading Studies
W.J. DeCoursey  Absorption with Chemical Reaction, Mass Transfer
E.N. Esmail  Liquid Coating, Fluid Mechanics, Modeling
G. Hill  Fermentation and Bioprocessing
D.G. Macdonald  Biomass Pyrolysis, Fermentation
D.-Y. Peng  Thermodynamics of Hydrocarbons and Petroleum
J. Postlethwaite  Corrosion Engineering
S. Rohani  Process Control, Crystallization and Mixing Phenomena with Fast Chemical Reactions, Dynamics and Control of Crystal Size Distribution, Diffusion-Reaction Modeling
C.A. Shook  Transport Phenomena, Slurry Pipelines

FOR INFORMATION, WRITE
M.N. Esmail, Head
Department of Chemical Engineering
University of Saskatchewan
Saskatoon, Saskatchewan
Canada S7N 0W0
UNIVERSITY OF SOUTH FLORIDA
TAMPA, FLORIDA 33620
Graduate Programs in Chemical Engineering
Leading to M.S. and Ph.D. degrees

Faculty
V. R. Bhethanabotla
J. C. Busot
S. W. Campbell
L. H. Garcia-Rubio
R. A. Gilbert
W. E. Lee
J. A. Llewellyn
C. A. Smith
A. K. Sunol

Research Areas
Applications of Artificial Intelligence
Automatic Process Control
Coal Liquefaction
Computer Aided Process Engineering
Computer Simulation
Crystalization from Solution
Electrolytic Solutions
Food Science and Engineering
Irreversible Thermodynamics
Mathematical Modelling
Membrane Transport Properties
Molecular Thermodynamics
Phase Equilibria
Physical Property Correlation
Polymer Reaction Engineering
Process Identification
Process Monitoring and Analysis
Sensors and Instrumentation
Statistical Mechanics
Supercritical Extraction
Surface Analysis
Thermodynamic Analysis of Living Systems

UNIVERSITY OF SOUTHERN CALIFORNIA
GRADUATE STUDY IN CHEMICAL ENGINEERING

• FACULTY •

W. VICTOR CHANG
(Ph.D., Ch.E., Caltech, 1976)
Physical properties of polymers and composites; adhesion; finite element analysis

JOE D. GODDARD
(Ph.D., Ch.E., U.C. Berkeley, 1962)
Rheology, continuum mechanics and transport properties of fluids and heterogeneous media

FRANK J. LOCKHART
(Ph.D., Ch.E., University of Michigan, 1943)
Distillation; air pollution; design of chemical plants (Emeritus)

RONALD G. MINET
(PhD, ChE, New York University, 1959)
Computer aided chemical process and plant design, catalysis, ceramic membranes (Adjunct)

CORNELIUS J. PINGS
(Ph.D., Ch.E., Caltech, 1955)
Thermodynamics, statistical mechanics and liquid state physics (Provost and Senior Vice President, Academic Affairs)

M. SAHIMI
(Ph.D., Ch.E., University of Minnesota, 1984)
Transport and mechanical properties of disordered systems; percolation theory and non-equilibrium growth processes; flow, diffusion, dispersion and reaction in porous media

RONALD SALOVEY
(Ph.D., Phys. Chem., Harvard, 1958)
Physical chemistry and irradiation of polymers, characterization of elastomers and filled systems; polymer crystallization

KATHERINE S. SHING
(Ph.D., Ch.E., Cornell University, 1982)
Thermodynamics and statistical mechanics; supercritical extraction

THEODORE T. TSOTIS
(Ph.D., Ch.E., University of Illinois, Urbana, 1978)
Chemical reaction engineering; process dynamics and control

IAN A. WEBSTER
(D.Sc., Ch.E., Massachusetts Inst. Tech., 1984)
Catalysis and reaction kinetics; transport phenomena, chemical reaction engineering, surface spectroscopy, biochemical engineering (Adjunct)

YANIS C. YORTSOS
(Ph.D., Ch.E., Caltech, 1978)
Mathematical modeling of transport processes; flow in porous media and thermal oil recovery methods.
CHEMICAL ENGINEERING at Stanford University

Stanford offers programs of study and research leading to master of science and doctor of philosophy degrees in chemical engineering, with a number of financially attractive fellowships and assistantships available to outstanding students. For further information and application forms, write to:

Admissions Chairman
Department of Chemical Engineering
Stanford, California 94305-5025

The closing date for applications is January 1, 1990

* Faculty *

Michel Boudart (Ph.D., 1950, Princeton) Kinetics and Catalysis
Curtis W. Frank (Ph.D., 1972, Illinois) Polymer Physics
Gerald G. Fuller (Ph.D., 1980, Cal Tech) Fluid Dynamics of Polymers and Colloidal Liquids
Alice P. Gast (Ph.D., 1984, Princeton) Physics of Dispersed Systems
Charles F. Gooch (Ph.D., 1984, U. Maryland) Biochemical Engineering
George M. Homsy (Ph.D., 1969, Illinois) Fluid Mechanics and Stability
Robert J. Madix (Ph.D., 1964, U. Cal-Berkeley) Surface Reactivity
Franklin M. Orr, Jr. (Ph.D., 1976, Minnesota) Enhanced Oil Recovery and Reservoir Engineering
Channing R. Robertson (Ph.D., 1969, Stanford) Bioengineering
John Ross (Ph.D., 1951, MIT) Chemical Instabilities

CHEMICAL ENGINEERING AT UNIVERSITY AT BUFFALO
STATE UNIVERSITY OF NEW YORK

FACULTY

P. Ehrlich T. J. Mountzias
R. J. Good E. Ruckenstein
R. Gupta M. E. Ryan
V. Hlavacek J. A. Tsamopoulos
K. M. Kiser C. J. van Oss
D. A. Kolke T. W. Weber
C. R. F. Lund R. T. Yang

RESEARCH AREAS

Adhesion
Adsorption
Applied Mathematics
Biochemical & Biomedical
Catalysis, Kinetics, & Reactor Design
Coal Conversion
Design and Economics
Fluid Mechanics
Polymer Processing & Rheology
Process Control
Reaction Engineering
Separation Processes
Surface Phenomena
Tertiary Oil Recovery
Transport Phenomena
Wastewater Treatment

Academic programs for MS and PhD candidates are designed to provide depth in chemical engineering fundamentals while preserving the flexibility needed to develop special areas of interest. The Department also draws on the strengths of being part of a large and diverse university center. This environment stimulates interdisciplinary interactions in teaching and research. The new departmental facilities offer an exceptional opportunity for students to develop their research skills and capabilities. These features, combined with year-round recreational activities afforded by the Western New York countryside and numerous cultural activities centered around the City of Buffalo, make SUNY/Buffalo an especially attractive place to pursue graduate studies.

For information and applications, write to:

Chairman, Graduate Committee
Department of Chemical Engineering
State University of New York at Buffalo
Buffalo, New York 14260
TEXAS A&I UNIVERSITY

Chemical Engineering
M.S. and M.E.

Natural Gas Engineering
M.S. and M.E.

FACULTY

R. N. FINCH, Chairman
Ph.D., University of Texas, P.E.
Phase Equilibria and Environmental Engineering

F. T. AL-SAADOON
Ph.D., University of Pittsburgh, P.E.
Reservoir Engineering and Production

F. H. DOTTERWEICH
Ph.D., John Hopkins University, P.E.
Distribution and Transmission

W. A. HEENAN
D.Ch.E., University of Detroit, P.E.
Process Control and Thermodynamics

C. V. MOONEY
M.E., Oklahoma University, P.E.
Gas Measurement and Production

R. A. NEVILL
B.S., Texas A&I University, P.E.
Natural Gas Engineering

P. W. PRITCHETT
Ph.D., University of Delaware, P.E.
Petrochemical Development and Granular Solids

C. RAI
Ph.D., Illinois Institute of Technology, P.E.
Reservoir Engineering and Gasification, Desulfurization

D. L. SCHRUBEN
Ph.D., Carnegie-Mellon University, P.E.
Transport Phenomena and Polymers

R. W. SERTH
Ph.D., SUNY at Buffalo, P.E.
Rheology and Applied Mathematics

Texas A&I University is located in Tropical South Texas, 40 miles south of the Urban Center of Corpus Christi, and 30 miles west of Padre Island National Seashore.

FOR INFORMATION AND APPLICATION WRITE:

W. A. HEENAN
Graduate Advisor
Department of Chemical & Natural Gas Engineering
Texas A&I University
Campus Box 193
Kingsville, Texas 78363

THE FACULTY

M. A. Abraham - Reaction kinetics, supercritical fluids
T. Arifman - Particulate science and technology, multiphase separation processes
R. L. Cerro - Capillary hydrodynamics, unit operations, computer-aided design
K. D. Luks - Thermodynamics, phase equilibria

F. S. Manning - Industrial pollution control, surface processing of petroleum
E. J. Middlebrooks - Environmental engineering
Y. T. Shah - Reactor design, coal liquefaction, mass transfer
K. L. Sublette - Fermentation, biocatalysis, hazardous waste treatment
R. E. Thompson - Oil and gas processing, computer-aided process design
K. D. Wisecarver - Fluidization, bioreactor modeling, mass transfer and adsorption in porous solids

FURTHER INFORMATION

If you would like additional information concerning specific research areas, facilities, curriculum, and financial assistance, contact the director of graduate programs.
The University of Tulsa, 600 South College Avenue, Tulsa, Oklahoma 74104 • (918) 631-2226
The University of Tulsa has an Equal Opportunity/Affirmative Action Program for students and employees

360

CHEMICAL ENGINEERING EDUCATION
ASPIRE TO NEW HEIGHTS

The University of Utah is the oldest state-run university west of the Missouri River. The University is world-renowned for research activities in medicine, science and engineering. The graduate Chemical Engineering program offers a number of collaborative, interdisciplinary research opportunities.

The University is located in Salt Lake City, the only metropolitan area in the country which is within 45 minutes of seven major ski areas and within a day's drive of five national parks. Entertainment in the city includes: resident ballet, symphony, and theater organizations; professional sports; and a variety of live music performances in public and private establishments throughout the city.

General areas of research:
- biotechnology
- catalysis
- combustion
- computer-aided design
- fossil-fuels conversion
- hazardous waste management
- minerals processing
- molecular modeling
- non-Newtonian fluid mechanisms
- polymer science

For information write: Director of Graduate Studies
Department of Chemical Engineering
University of Utah
Salt Lake City, Utah 84112

Graduate Studies in Chemical Engineering
UNIVERSITY OF UTAH

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- T. D. GIORGIO (Ph.D., Rice University)
- T. M. GODBOLD (Ph.D., North Carolina State University)
- K. A. OVERHOLSER (Ph.D., P.E., U. of Wisconsin, Madison)
- P. J. ROSELLI (Ph.D., University of California, Berkeley)
- J. A. ROTH (Ph.D., P.E., University of Louisville)
- K. B. SCHNELLE, JR. (Ph.D., P.E., Carnegie-Mellon Univ.)
- R. D. TANNER (Ph.D., Case Western Reserve University)

DEPARTMENTAL RESEARCH AREAS
- Atmospheric Diffusion Analysis
- Biological Transport Processes
- Biomedical Applications
- Chemical Process Simulation
- Coal Conversion Technology
- Coal Surface and Pore Structure Studies
- Enzyme Kinetics and Fermentation Processes
- Physical and Chemical Processes in Wastewater Treatment

Further Information: Kenneth A. Debelak, Director of Graduate Studies
Chemical Engineering Department
Box 1700, Station 9
Vanderbilt University
Nashville, Tennessee 37235
WAYNE STATE UNIVERSITY

GRADUATE STUDY in CHEMICAL ENGINEERING

- D. A. Crowl, PhD: safety and loss prevention • computer applications
- H. G. Donnelly, PhD: thermodynamics • process design
- E. Gulari, PhD: transport • laser light scattering
- R. H. Kummler, PhD: environmental engineering • kinetics
- C. B. Leffert, PhD: energy conversion • heat transfer
- C. W. Manke, Jr., PhD: polymer engineering
- R. Marriott, PhD: computer applications • nuclear engineering
- J. H. McMicking, PhD: process dynamics • mass transfer
- R. Mickelson, PhD: polymer science • combustion processes
- S. Ng, PhD: polymer science • catalysis
- E. W. Rothe, PhD: molecular beams • analysis of experiments
- S. Salley, PhD: biosystems modelling • kinetics
- S. K. Stynes, PhD: multi-phase flows • environmental engineering

CONTACT: Dr. Ralph H. Kummler, Chairman
Department of Chemical Engineering
Wayne State University
Detroit, Michigan 48202

WEST VIRGINIA INSTITUTE OF TECHNOLOGY
LEONARD C. NELSON COLLEGE OF ENGINEERING

New Masters Programs in Control Systems and Environmental Engineering

West Virginia Institute of Technology's Leonard C. Nelson College of Engineering is pleased to announce new programs leading to the Master of Engineering degree in Control Systems and Environmental Engineering. These are unique interdisciplinary programs which include industrial internship periods. Both of the programs are ideally suited to prepare students for professional engineering practice.

The Control Systems program is structured primarily for students with chemical, electrical, or mechanical engineering undergraduate degrees, while the Environmental Engineering program is designed primarily for chemical and civil engineers. Either program should required 18 months to complete, which includes two summers of internship at a cooperating company. We plan to provide a stipend of $15,000-$18,000 which will be supplied by the cooperating company.

If you are a superior student with an interest in helping us while we help you, write:

Dr. E. H. Crum
Director of Graduate Program
West Virginia Institute of Technology
Montgomery, WV 25136
UNIVERSITY OF WYOMING
Chemical Engineering

We offer exciting opportunities for research in many energy related areas. In recent years research has been conducted in the areas of kinetics and catalysis, adsorption, combustion, extraction, water and air pollution, computer modeling, coal liquefaction, and in-situ coal gasification.

The University of Wyoming is located in sunny and dry Laramie (pop. 25,000), 25 miles from Colorado. Access to superb outdoor activities and to the Denver area is excellent.

Graduates of any accredited chemical engineering program are eligible for admission, and the department offers both an M.S. and a Ph.D. program. Financial aid is available, and all recipients receive full fee waivers.

THE UNIVERSITY OF BRITISH COLUMBIA

The Department of Chemical Engineering invites applications for graduate study from candidates who wish to proceed to the M.Eng., M.Eng. (Pulp & Paper), M.A.Sc., or Ph.D. degree. For the latter two degrees, Assistantships or Fellowships are available. NOTE:

AREAS OF RESEARCH

Air Pollution
Biochemical Engineering
Biomedical Engineering
Coal, Natural Gas and Oil Processing
Electrochemical Engineering
Electrokinetic and Fouling Phenomena
Fluid Dynamics
Fluidization
Heat Transfer
Kinetics
Liquid Extraction

Magnetic Effects
Mass Transfer
Modelling and Optimization
Particle Dynamics
Process Dynamics
Pulp & Paper
Rheology
Rotary Kilns
Separation Processes
Spouted Beds
Sulphur
Thermodynamics
Water Pollution

Inquiries should be addressed to:

Graduate Adviser
Department of Chemical Engineering
THE UNIVERSITY OF BRITISH COLUMBIA
Vancouver, B.C., Canada V6T 1W5

For more information contact:
Dr. Robert D. Gunn, Head
Dept. of Chemical Engineering
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