Featuring . . .

Arvind Varma
of Notre Dame

. . . plus articles on

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When Arvind Varma was awarded the University of Notre Dame’s College of Engineering Outstanding Teacher of the Year Award for 1990-91, his students praised him as “an excellent teacher both in and out of the classroom,” and said he showed a “great interest in his students” and was “willing to be a friend and a mentor.” They cited his extensive availability, saying it was “a rare and valuable opportunity to work with a person with such great character and work ethic. He will be the professor whom we will vividly remember twenty years from now, and his influence will be matched by few in our lifetime.”

The award and the citation that accompanied it were gratifying to Arvind, who believes that the most important thing a teacher can be is a good model for the students. “Whether you are in the classroom or doing research, you must always do things the right way,” he says. “A teacher should not just impart information, but should also teach students how to think, how to live. You need to teach critical analysis, so that they are able to ask questions, to make decisions on their own. You can rely on people and other sources for information, but you should be able to analyze on your own to make decisions.” That ability to analyze is what he hopes he has taught his students.

Carmo J. Pereira, a former student who is now a Principal Consultant at DuPont Engineering, believes he learned that ability as Varma’s student. “When I first met Professor Varma, he had just arrived at Notre Dame after two years in industry. I am a practicing reaction engineer today in large part due to him. His love for reaction engineering, his great attention to detail, and his dedication to the profession

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"As a young faculty member in the late 1970s, and
As a graduate student in the late 1960s, and
As an undergraduate student in the mid-1960s."
[Arvind] says,

“A teacher should not just impart information, but should also teach students how to think, how to live. You need to teach critical analysis, so that they are able to ask questions, to make decisions on their own.

are truly contagious! I have been greatly influenced by Professor Varma’s desire to excel, and I have attempted to follow his example.”

Another former student, Bala Subramaniam (now a chaired professor of chemical and petroleum engineering at the University of Kansas in Lawrence) says, “Professor Varma’s research accomplishments are well known and recognized. What is probably not as well known is that Professor Varma is also a gifted teacher with exemplary dedication and excellence in educating his students.” He adds, “His lectures are intellectually stimulating, characterized by careful preparation and energetic delivery. Professor Varma brought to his class the latest research developments from his program as well as others. This allows students to gain a better appreciation of creativity, which in turn inspires them to be creative. He is very accessible to his students, and whenever interacting with them either in or outside class, he creates an atmosphere that promotes the students’ desire to learn and to excel. Personally, these experiences have helped shape my teaching philosophy and methods to a great extent.”

Arvind was born in Ferozabad, U.P., India, the fourth of seven children. He had always been a good student and, due to double promotions, was only 15 years old when he graduated from high school in 1962. This made choosing a college difficult because most of the schools in India had age restrictions and required incoming freshmen to be at least 17 or 18 years old. The Indian Institutes of Technology were just starting then and were already prestigious, but they too had age restrictions.

Arvind had done well in chemistry and mathematics in high school and was looking at chemical engineering on the advice of his father, who was a civil engineer working in government service. When Arvind learned that Panjab University in Chandigarh (one of the schools without an age restriction) had recently started a chemical engineering program with American collaboration, he applied there and was accepted. It was a unique situation in that the engineering college affiliated with the school had the other engineering disciplines on its own campus, but the new chemical engineering department was autonomous and was housed on the main university campus.

The chairman of the department was Professor B. Ghosh. He was young, outstanding, and bright. Recently returned from Carnegie Tech (now Carnegie-Mellon), he was a thoughtful teacher, and through him, Arvind was exposed to a more American style of teaching. Professor Ghosh’s classes were more open and discussion-based, and he didn’t insist on such a strict student/teacher division. It was at this time that teaching as a profession began to appeal to Arvind.

“The idea of standing up in front of class, explaining things, talking about what you knew, was very appealing to me,” Arvind says. “I decided during my freshman year to be a college teacher.”

When he finished his undergraduate work, Arvind was still only 19 years old and was anxious to come to North America for his graduate work. His parents weren’t too keen on his leaving the country, but he was ready for new challenges. He applied to a few places in Canada and eventually chose the University of New Brunswick, where he would have the chance to work with Frank Steward in combustion of solid fuels.

At the University of New Brunswick he was exposed to even more of the Western style of teaching, further convincing him that he wanted to be an educator. But in his second year of graduate school, Frank Steward took a UNESCO appointment, and Arvind decided to change schools to pursue his doctorate. The University of Minnesota was rated very highly then, as it is now, and he was accepted and awarded an assistantship there.

During the late 1960s and 1970s, the University of Minnesota was an exciting place to be. A great deal of research was being done in the area of analysis of chemical engineering systems, particularly mathematical analysis. This effort was led by Professor Neal Amundson, who was department head and also Arvind’s thesis advisor. Amundson had gathered together a top-notch faculty, many of whom had degrees in the sciences or math rather than in chemical engineering. At this same time, the Mining and Metallurgical Engineering Department was closing down and materials science was brought into chemical engineering. This mixture produced an emphasis on the fundamental scientific aspects of chemical engineering—the engineering science approach—in which there is an application of surface chemistry, biology, mathematics, and physics to chemical engineering problems. This mixture of disciplines is more common now, especially in research groups, but it was very unusual at that time.
At the University of Minnesota, Arvind was influenced greatly by both Professor Neal Amundson and Professor Rutherford Aris. Besides being an innovative leader, Amundson was a brilliant teacher and researcher. He taught a two-hour course on mathematical methods in chemical engineering twice a week and did all his complex computations on the chalkboard without any notes. Aris was a great scholar and writer, very fluent with words and widely published. He was a soft-spoken, kind gentleman. Where Amundson was Arvind’s model of an innovator and teacher, Aris was his model of a scholar.

In 1971, Arvind married his wife Karen, then a senior majoring in biology at the University of Minnesota. A few days after getting married, they spent six weeks in India, meeting his family and seeing the country. Arvind received his PhD in 1972. His thesis on “Analysis of Tubular Reactor Multiple Steady States and Their Stability” generated a number of articles. After he was awarded his doctorate, Arvind stayed on at the University of Minnesota as a temporary assistant professor for one year, doing limited teaching while working on research. During this period he got to know Professors Amundson and Aris even better, as well as a number of other faculty members.

Arvind firmly believed that to be a good teacher, one needed industrial experience (as Amundson and Aris had), so when he was ready to leave the University of Minnesota he interviewed both in academia and in industry. After considering offers from a number of sources, he went to work as a senior research engineer for Linde Research of Union Carbide in Tarrytown, New York, where he did research in gas separations.

The research at Union Carbide was very different from that which Arvind had done for this thesis, but that was part of its appeal since it meant his experience would become even broader. He was hired as a part of the Process Research Group, a newly formed unit that was looking into novel methods of gas separation processes. Some of the projects that he worked on in their initial conceptual stages were a new process for breathing oxygen on aircraft, a new type of cryogenic insulation using thin evacuated glass microspheres, a zeolite slurry-based continuous gas separation process, and a parametric pumping system for an air separation process for producing oxygen for medical purposes. A number of these projects subsequently became commercial successes.

During this period, Karen and Arvind also became proud parents of their first child, Anita, born in 1974. Karen had worked as a laboratory assistant in microbiology since her graduation two years earlier, but now gave up her career to become a full-time mother.

In 1975, after two years at Union Carbide, Arvind received an offer from the University of Notre Dame. The chemical engineering department there was well known due to the work in catalytic reaction engineering done by James Carberry and Ernest Thiele (who was no longer at Notre Dame but who had added greatly to the stature of the department) as well as the work in thermodynamics and phase equilibria being done by James Kohn and Kraemer Lukas. Also, the department’s chairman, Julius Banchero, was a well-known educator who was supportive of young faculty. Arvind decided to make the change to academia and was further convinced that the decision was a good one when Roger Schmitz came from the University of Illinois in 1979 to take over as department chair upon Banchero’s retirement. Arvind quickly progressed through the ranks, becoming a full professor in 1980, the same year that his younger daughter, Sophia, was born.

In 1982, Arvind became department chair himself when Roger Schmitz went on to become engineering dean. Although Arvind was young for the position, he had definite ideas he was eager to implement and, under his leadership, the department grew. During his tenure, Mark McCready (the current department chair), David Leighton, and Hsueh-Chia Chang (who served as chair after Arvind) all joined the faculty.

When he was chair, Arvind chose to teach the “Introduction to Chemical Engineering” course himself because he thought it was important for the chair to be visible to the new students in the department. He also brought team teaching to the undergraduate labs, with part of the faculty teaching the fall semester lab for seniors and another part teaching the spring lab for juniors. This had the dual effect of making it more interesting for the faculty to teach and encouraging camaraderie as they worked together. It was also good for students to have contact with a number of faculty members. The senior design course is also team taught, so every member of the faculty instructs in one of these three courses every year. All three courses have written and oral reports due at the end of the semester. By implementing his ideas, Arvind helped to create an atmosphere of high standards for
teaching and research.

Mark McCreary, chair of the department, notes another aspect of Arvind’s leadership. "While Arvind is well known for his mentoring of graduate students and his efforts to enhance these activities campus wide, he has also mentored a number of current faculty at Notre Dame. He provided a great deal of guidance to me during my first few years here. He helped with proposal and paper writing, encouraged my participation in departmental committees, and made sure that my views were heard. His efforts greatly enhanced my development as a junior faculty member."

In order to devote full time to teaching and research, Arvind decided to leave the department chair position in 1988. Within a few months of this decision, he was named the first occupant of the Arthur J. Schmitt endowed chair professorship, a position he still holds.

All of Arvind’s research involves undergraduate, graduate, and post-doctoral students, true to his vision of an educator. When he was awarded the 1997 Burns Graduate School Award from the University of Notre Dame this past May, the citation noted, in part, that he is “a quintessential professor who excels in all phases of academic life and for whom there is no boundary between teaching and research.”

In his twenty-three years at Notre Dame, twenty-seven students have completed their doctoral dissertations under his direction, and several more are currently in progress. Every dissertation has resulted in coauthored publications in leading journals and typically in one or more paper presentations at technical meetings. One of his students, Jean-Pascal Lebrat received the 1993 Graduate School Award in Engineering in recognition of the quality of his dissertation research. Furthermore, largely through Arvind’s efforts in counseling and mentoring, his former students have been very successful professionally in both industry and academia. Of his former PhD and post-doctoral students, eighteen are in academic positions at institutions around the world.

“As a mentor, Professor Varma led and taught by example. His enthusiasm for his research program was infectious and evident during the weekly research group meetings,” Bala Subramaniam says.

Arvind’s early research involved various topics in chemical and catalytic reaction engineering, including diffusion-reaction in catalyst pellets, reactor modeling and optimization, gas-liquid reactors, and three-way catalysis for automobile exhausts. Beginning in the early 1980s, his focus was mainly in two areas. One area was the optimal distribution of catalyst in pellets, in which the problem addressed is “How should a fixed amount of catalyst be distributed in a pellet to optimize some specified performance index?” This problem is common to all reactions that use supported catalysts. In systematic and innovative theoretical and experimental work, Arvind and his students have shown that the optimal distribution is a Dirac-delta function, i.e., the catalyst should be deposited at a specific radial position within the pellet. He has also developed experimental methods for preparing such catalysts. This work has direct implications for rational catalyst design and manufacture.

The other area of Arvind’s research during this period was parametric sensitivity and runaway in chemical reactors. In certain regions of operating conditions, chemical reactors exhibit parametric sensitivity whereby small changes in input parameters lead to large changes in output variables. This behavior is common to all exothermic reaction systems. Determining these regions is of substantial interest because such behavior leads to deleterious reactor performance. By original and penetrating analysis, confirmed by experiments, Arvind and his research group have provided rigorous and easily applicable criteria for identifying the regions of parametric sensitivity and runaway for a variety of reacting systems.

For the last six to eight years, Arvind’s research has been in the area of materials, specifically the combustion synthesis of materials. This is a large research program for mechanistic studies of combustion synthesis: What is the mechanism by which advanced materials such as ceramics, intermetallics, and composites are synthesized by the novel technique called combustion synthesis? How does the reaction occur? How is the product material formed? How can the microstructure of the material be controlled as it is being synthesized? Because the microstructure affects the properties of the material, by understanding the mechanism of the reaction and how the microstructure is formed, Arvind hopes to gain an understanding of the control over what the properties of the material are going to be. His funding for this research is from NSF and NASA.

In the NASA program, Arvind is looking at effects of gravity on combustion synthesis of materials. Both the NSF and NASA programs have produced some unique results and new research techniques. One such technique, producing promising results, is the high-speed microvideo recording of the combustion wave front.

“We are able to expand the wave front through magnification, using a long focus microscope attached to a high-speed video camera,” Arvind says. “We can increase the spatial resolution up to 800 times and can record up to 10,000 frames per second.”

Arvind and his students can watch just how the reaction is occurring and can see many of the details of combustion wave propagation, leading to a better understanding of how the wave front propagates in heterogeneous reaction mixtures that are used for synthesizing advanced materials. They have the only facility in the world for doing this and are at the forefront of developing new techniques for understanding how such reactions occur. Using this novel technique, Arvind and his research group have identified new modes of
propagation that have never been witnessed before—they call it a scintillating reaction wave. In recent work, they have shown that in many instances, the reaction initiates ahead of the wave front and sparks appear. They are the first precursor of the main reaction that occurs a few milliseconds later.

Another direction of Arvind's current research is inorganic membranes. With funding from the National Science Foundation and from industry (primarily Union Carbide), he is studying various types of inorganic membranes—both metal composite membranes in which a thin (a few microns thick), dense, metal film is deposited on a porous support, as well as ceramic membranes with controlled pore size and catalytic activity distributions. He and his students have developed some novel techniques, such as the use of osmosis in conjunction with electrolyss plating. Using this idea, they have synthesized high-flux thin metal composite membranes for both high temperature reaction and separation processes.

In his current research, Arvind is applying the principles of chemical engineering and novel experimental techniques. His approach of combining theory and experiments, and of determining the influence of processing variables on the resulting microstructure and the reaction mechanism and extent, is having a strong impact on the materials synthesis field. He is frequently the only, or one of only a few, chemical engineers invited to speak at conferences related to the reaction synthesis of advanced materials. Examples include the TMS Annual Meeting in 1991 and all four International Symposia on Self-Propagating High Temperature Synthesis held in the former USSR (1991), Honolulu (1993), China (1995), and Spain (1997). His plenary lecture on the “Combustion Synthesis of Advanced Materials” at the 1992 International Symposium of Chemical Reaction Engineering has received considerable acclaim and attention as a landmark summary of research in this area. His forthcoming monograph will update this work and has been praised already as “the seminal review on combustion synthesis.”

Arvind has published extensively in collaboration with Massimo Morbidelli, now a chaired professor at ETH in Zurich, Switzerland. Massimo came to Notre Dame in 1979 on a fellowship from Italy. He stayed only six months, but wrote four papers while he was here and made a lasting impression on Arvind, who felt that he had great potential and encouraged him to get his advanced degree.

His influence made a difference to Morbidelli. “I decided to come back for my PhD,” Massimo recalls, “But since I was a researcher at Politecnico de Milano, I could not do it on a full-time basis. It was Dr. Varma who arranged (with the help of the department chairman at that time, Dr. Roger Schmitz) a semi-non-resident PhD program for me at Notre Dame.”

Since then, Massimo and Arvind have written some forty articles and two books together, making their collaboration one of the longer standing ones in academia. Their textbook Mathematical Methods in Chemical Engineering (Oxford University Press) was published earlier this year, and Parametric Sensitivity in Chemical Systems (Cambridge University Press), written jointly with research associate Hua Wu, was completed this past August and will be published early next year as part of the Cambridge Series in Chemical Engineering, of which Arvind is the founding editor.

“I have continued my collaboration with Dr. Varma for almost twenty years now,” Massimo says, “And I find it always more exciting, although we have now evolved in different research areas. But even recently, when after long hours together, one in front of the other at the same table, reviewing our math book when we finished it, I felt the same sense of accomplishment as when we finished our first paper in 1979. I really felt I did something to my best, without saving energies. This was in fact the program that Dr. Varma stated many years ago when starting the ‘book adventure.’ He’d told me, ‘... and at the end we will sit together, read each page of the book, and leave there each word only if we like it.’ And it has been done. This is really a great teaching for how to proceed in science, and I have seen this teaching penetrating all my students who later came to work for longer or shorter periods of time with Dr. Varma from Italy: Alberto Servida, Roberto Baratti, Giacomo Cao, Hua Wu, Marco Apostolo, and others.

“Professor Varma has made significant contributions to reaction engineering,” Carmo Pereira says. “His work on optimizing catalyst intraparticle profiles and on high temperature synthesis is seminal, and he has received many honors for his work, including AIChE’s prestigious Wilhelm Award.”

Arvind has also found time to serve the University of Notre Dame as well as many professional organizations. In 1992, he was awarded a Special Presidential Award by the University for his “indefatigable energy in research, writing, and all activities that engage his sharp mind and for serving simultaneously on a large number of university, college, and departmental committees.” He was a member of the University’s Executive Committee of the Academic Council for three years, served on the Academic and Faculty Affairs Committee of the Board of Trustees for three years, and was chairman of the Task Force on Research Systems, as well as other committees. He is a founding director of the Catalysis and Reaction Engineering Division of AIChE, serving a three-year term; a current member of the AIChE Awards Committee, serving a five-year term; and has organized and chaired numerous technical sessions at national and international conferences.

“Professor Varma’s well-balanced contributions in teaching, research, and service are truly remarkable and make him the consummate professional and excellent role model that he is,” Bala Subramaniam says. “The fact that several of his students have gone on to assume successful careers in aca-
Arvind and Karen, along with his research group and their terrier Frankie, at a recent get-together at their home.

A family photograph in traditional Indian dress on the occasion of older daughter Anita’s marriage to Ken (also a chemical engineer) in May of 1997. On the left is younger daughter Sophia, currently a high school senior.

demia and in major companies is a testament to his excellent training and positive influence on his students.”

Roger Schmitz, Keating-Crawford Professor of Chemical Engineering at Notre Dame, has worked with Arvind for eighteen years and says, “I find it difficult to identify Arvind’s strongest points because he excels in virtually every respect in his professional and personal life. Few individuals can match the combination of traits—dedication to academic work, motivation to excel, adherence to high standards of quality, selflessness in service to the university and the profession, boundless energy and capacity for work—that make him a valuable member of our faculty and of our profession.

Massimo Morbidelli finds it hard to pick just one outstanding attribute from the many things that he has learned from Arvind. “The one that I am not sure I have learned, but one that I certainly admire, is his honesty in science. By this I mean not only of a moral but also of an intellectual nature. In particular, stating and writing a concept only after he has tried by all means to clarify and to penetrate it. I do not recall a single time when he said, ‘Well, it doesn’t matter....’ He always wanted to go as deep as possible in all aspects of a problem and in all details, which was not always easy for grad students. Another aspect was his profound knowledge of the literature and his capability of always giving appropriate credit to all other researchers.”

“Above everything else, Professor Varma is an outstanding individual who treats his students with courtesy and fairness,” Subramaniam adds. “Among the many memories that I cherish from my graduate students days at Notre Dame are the cookouts and get-togethers at his house. Professor Varma and his wife, Karen, are extremely gracious hosts and treated students to a variety of culinary dishes, including, of course, spicy Indian food! The friendships and associations forged there have been long-lasting. At the AIChE annual meetings, Professor Varma makes it a point to organize a dinner-outing with his former students. These outings have become a pleasant forum for developing new friendships as well as reminiscing about old times.”

Arvind’s commitment to his students extends beyond just the schooling years. He has truly lived his belief of being a model for them all.

In spite of the intense agenda of work and professional activities to which he holds himself, Arvind has managed to balance his time and interests between professional and family obligations. He is quick to express pride in the accomplishments of Karen and his daughters, and he considers his family to be the most important element in his life. Anita is a 1996 Notre Dame graduate in political science. She worked for one year as a volunteer in the Americorps Vista project and is currently a first-year law student in Washington, DC. Earlier this year, she married Ken Motolenich, a Notre Dame chemical engineering graduate with a master’s degree in environmental engineering from MIT. Their wedding included both church and traditional Hindu ceremonies. Sophia is currently a senior in high school, busy with college applications, and has strong interests in drama and musical theatre. Anticipating more free time in the future, Karen has been preparing for the last several years for a teacher’s certificate in high school science and expects to start her teaching career next fall. She is also an accomplished opera singer.
Wayne State University

The Detroit metropolitan area is one of the largest in the United States. Businesses of every size and kind, including the research and production facilities—and world headquarters—for the "Big Three" U.S. automobile companies and many of the high-tech companies that supply them, are within a short drive of one another. The excitement of these business and research opportunities, combined with the natural attractions of the Great Lake State, bring nonstop traffic to the nearby airport as people from around the nation and around the world stream into southeastern Michigan.

Amid this flurry of activity is Wayne State University and its Department of Chemical Engineering and Materials Science. The department, chaired by Esin Gulari, has 200 undergraduate students, 120 graduate students, and 15 full-time faculty members. Students make full use of the research and employment possibilities presented by a large metropolitan setting and the facilities offered at a major urban research university—all while learning in small and intimate departmental classes more reminiscent of a private institution.

THE UNIVERSITY AND THE METROPOLITAN DETROIT AREA

Wayne State University has the advantage of being in the middle of it all, literally and figuratively. Its location in the heart of metropolitan Detroit gives both faculty members and students the chance to explore great variety in the area’s cultural and business communities. Metropolitan Detroit has a worldwide reputation as a dominant manufacturing hub, and it is also gaining recognition as a center for technological innovation. Through various co-op programs and research collaborations between hundreds of these companies and Wayne State, students have the freedom to incorporate on-the-job training into their overall education.

Most of Wayne State’s 31,000 students commute to WSU from the city and its suburbs, but thousands also come from other states and countries. The campus has a richly diverse faculty and student body, bringing different and unique perspectives to the classroom.

In addition, the metropolitan Detroit area has all of the cultural attractions expected in an urban environment (most within easy walking distance of the WSU campus) along with the benefits of various recreational areas, many situated on one of the state’s 11,000 lakes. Sports are also prominent in Michigan. Detroit’s professional hockey, football, baseball, and basketball teams draw some of the nation’s most enthusiastic audiences.

Beyond its prime location, Wayne State University has earned a reputation for its excellent educational, research, and community-service programs. For example, Wayne State is ranked as a Carnegie I Research University, placing it among the top 88 universities nationwide to hold the prestigious designation. Conferred by the Carnegie Foundation
for the Advancement of Teaching, this title is reserved for universities that meet highly selective criteria for emphasizing research in addition to undergraduate and graduate education.

Wayne State University is in the middle of it all, and the Department of Chemical Engineering and Materials Science has taken its place as one of the university’s premier departments.

**THE DEPARTMENT**

Students and faculty members alike find the Wayne State University Department of Chemical Engineering and Materials Science to be an ideal size—small enough to engender a sense of community, yet large enough to provide varied curricular and research opportunities.

The sense of community is most clearly evident among the faculty members, who often meet in groups to take casual lunches together, or who spend time in one another’s offices discussing progress in the lab or in the classroom. This atmosphere has also given rise to a number of stimulating research collaborations among faculty members.

The department itself is a collaboration of sorts. In 1993, chemical engineering and materials science, two separate but complementary disciplines, extended the good repertoire they had already developed and merged. Opportunities arose for cross-listed courses and multidisciplinary laboratories.

For students, the dual-disciplined department also opens doors for them to have two or more faculty mentors. In addition, students can learn from classmates and faculty members in the other discipline and begin to see their field through others’ eyes. Departmental graduates find this kind of insight particularly useful in the workplace.

The curriculum in the department is wide in scope. The undergraduate program includes courses that promote an understanding of physical, biological, and chemical operations and processes. Graduate students can choose from a breadth of electives toward the MS and PhD in chemical engineering, the MS and PhD in materials science and engineering,
and the MS in hazardous waste management. Specialized training is also available, including graduate certificates in polymer engineering, environmental auditing, and hazardous waste control.

Outside of the classroom, students make use of modern laboratory facilities throughout the Engineering Building, computer workstations in the Engineering Building and around the campus, and a complete university research library. The newly opened undergraduate library provides ample study areas and extensive computer equipment for student use.

THE UNDERGRADUATE PROGRAM

Going well against the grain, WSU’s Department of Chemical Engineering and Materials Science brings together the lower tuition rates of a public university, the well-equipped laboratories of a major research institution, and the small undergraduate class sizes of a private college. This combination presents an excellent environment for its students.

Class sizes are generally in the range of 20 to 25 students. In this more intimate setting, students feel comfortable meeting one-on-one with their professors and getting to know their classmates. Students commonly create informal groups to work out complex study problems or to prepare for tests, both very effective learning tools.

Research is also a meaningful aspect of the undergraduate educational experience within the department. Undergraduate students can elect courses that involve research programs or can take part in one of the many active projects of the faculty members by accepting student research assistantships. Either way, participating students can augment their course work (and their resumes) both by working closely with professors who are conducting related research and by sharing a laboratory with highly trained graduate students and with other like-minded undergraduate students.

While not a requirement, at least half of the undergraduate students take part in the department’s well-developed Cooperative Education Program. The unique relationship between WSU and local industry helps to create the diverse opportunities presented through the program. Participating students alternate full-time study terms with full-time work assignments in nearby companies. The location of the university makes it easy for the students to commute from the workplace to campus, and the department’s accommodating course schedule has day and evening courses to meet the needs of students in the program.

Another unique educational venture in the department is the undergraduate seminar series that brings in scientists from industry and academic institutions along with now-working alumni. During each of the three semesters of seminars the undergraduate students are required to attend, each student prepares a memo for the department chair about his or her educational progress and thoughts about the overall departmental program. The exercise not only allows the students to evaluate their goals, but it also helps the chair to prepare for the department’s future.

THE GRADUATE PROGRAM

The graduate program at Wayne State’s Department of Chemical Engineering and Materials Science is actually two programs: one designed for doctoral students pursuing full-time thesis research and another for master’s students pursuing part-time course work.

The opportunity for graduate thesis research is abundant. Students, who come to Wayne State from the United States and all over the world, choose a research advisor from an internationally recognized faculty of active scholars. Research topics available are particularly diverse and span many of the “hot” new areas of chemical engineering, including supercritical processing, interfacial phenomena, advanced materials processing, and bioengineering.

Strong federal, industrial, and internal support has resulted in the graduate facilities at Wayne State being second to none. For example, the department possesses several state-of-the-art instruments, including atomic force microscopes, an integrated optical biosensor, a rheo-optical FTIR spectrometer, various shear and extensional flow rheometers, and an excimer-laser-based imaging system. Additionally, connections with other research institutes on campus and with local industries provide access to unique chemical and material characterization facilities. Competitive stipends typically support the students.

Another unique feature of the Wayne State graduate program is the course-work master’s degree program. Students, who typically are working engineers from the local area, are able to complete their degrees in a reasonable time due to flexible course offerings and the university’s convenient location. The department designs many of the courses in

Professor Esin Gulari and Research Assistant Vikhar Khan peering at polymer phases.
collaboration with industry to ensure that the students are best trained to deal with the contemporary issues of the discipline. As evidence of the program’s success, Wayne State is currently the nation’s number-one conveyor of master’s degrees in chemical engineering.

**GRADUATE CERTIFICATE PROGRAMS**

Three graduate certificate programs round out the department’s curriculum: polymer engineering, environmental auditing, and hazardous waste control.

The Graduate Certificate Program in Polymer Engineering provides specialized education for working engineers and scientists. The program includes core courses and electives (such as composite materials, polymer rheology, and polymer kinetics) that are developed with input from professionals in industry. Students can complete the program in as little as one year.

Designed with working professionals in mind, the Hazardous Waste Control and Environmental Auditing programs have a combination of core courses and more specialized electives. The Graduate Certificate Program in Hazardous Waste Control teaches state-of-the-art methods for management, control, and disposal of a broad range of hazardous substances, wastes, and materials. Students also gain practical knowledge in meeting government guidelines for waste management. The Graduate Certificate Program in Environmental Auditing covers the management, assessment, and auditing of facilities and properties, hazard identification, exposure, analysis and risk characterization, regulatory noncompliance analysis, sources of liability, and alternatives for corrective action.

**RESEARCH**

Research conducted in the WSU Department of Chemical Engineering and Materials Science falls into three expansive areas: materials processing and synthesis; pollution prevention and control; and bioengineering. Many of the department’s faculty members have interests that combine more than one area (see Table 1, next page).

The research of **Esin Gulari** and **Charles Manke** recently gained public attention when they received the highly regarded Henry Ford Technology Award. They became the first non-Ford Motor Company employees to earn that distinction. The award recognized their work in reducing misting of metal-working fluids in Ford’s manufacturing plants. The two professors worked closely with all three of the U.S. automotive companies, even using company research laboratories and manufacturing plants to refine and verify their results.

Both **Howard Matthew** and **Guang-Zhao Mao** hold National Science Foundation Faculty Early Career Development Program (CAREER) Awards. This prestigious award recognizes faculty members who embody the excitement of
TABLE 1
Faculty: WSU’s Department of Chemical Engineering and Materials Science
(Additional information through the CHE and MSE option on the web page at http://www.eng.wayne.edu)

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution and Year</th>
<th>Research Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>John Benci</td>
<td>PhD, University of Pennsylvania, 1989</td>
<td>Deformation and fracture of materials, High-temperature mechanical properties of alloys, intermetallic compounds, and ceramics</td>
</tr>
<tr>
<td>Esin Gulabi</td>
<td>PhD, California Institute of Technology, 1973</td>
<td>Thermodynamics and transport properties of polymer solutions and melts, Processing of polymers with supercritical fluids, Light-scattering-based particle and drop-sizing techniques</td>
</tr>
<tr>
<td>Yilun Huang</td>
<td>PhD, Kansas State University, 1992</td>
<td>Pollution prevention and waste minimization, Process design and synthesis</td>
</tr>
<tr>
<td>Rangaramanujam Kannan</td>
<td>PhD, California Institute of Technology, 1994</td>
<td>Dynamics of polymeric systems and interfaces, Rheo-optical spectroscopy and scattering techniques</td>
</tr>
<tr>
<td>Ralph Kummler</td>
<td>PhD, Johns Hopkins University (1966)</td>
<td>Modeling of combined sewer overflows and sediments, Chemical kinetics, Computer simulations</td>
</tr>
<tr>
<td>Charles Manke</td>
<td>PhD, University of California-Berkeley, 1983</td>
<td>Polymer processing and rheology, Molecular dynamics and kinetic theory of polymeric liquids</td>
</tr>
<tr>
<td>Guang-Zhao Mao</td>
<td>PhD, University of Minnesota, 1994</td>
<td>Opto-electronic properties of thin films and crystals, Self-assembly of polymers and surfactants, Colloidal stability of waterborne paints, Real-time imaging of surface phenomena at the molecular level</td>
</tr>
<tr>
<td>Howard Matthew</td>
<td>PhD, Wayne State University, 1992</td>
<td>Tissue engineering and biomaterials, Artificial organ substitutes</td>
</tr>
<tr>
<td>James McMicking</td>
<td>PhD, Ohio State University, 1961</td>
<td>Correlation of thermodynamic data</td>
</tr>
<tr>
<td>Simon Ng</td>
<td>PhD, University of Michigan, 1985</td>
<td>Heterogeneous catalysis, Polymer kinetics, Spectroscopic and thermal analysis of material surfaces</td>
</tr>
<tr>
<td>Susil Putatunda</td>
<td>PhD, Indian Institute of Technology, Bombay, 1983</td>
<td>Effects of microstructure on fatigue, Fatigue toughness, Creep in metals and alloys</td>
</tr>
<tr>
<td>Matthew</td>
<td>PhD, Wayne State University, 1992</td>
<td>Tissue engineering and biomaterials, Artificial organ substitutes</td>
</tr>
<tr>
<td>Erhard Rothe</td>
<td>PhD, University of Michigan, 1959</td>
<td>Applications of high-powered UV lasers, Machining of electronic chips, Diagnostics of internal combustion</td>
</tr>
<tr>
<td>Steven Salley</td>
<td>PhD, Detroit University, 1976</td>
<td>Biochemical/medical engineering, Design of artificial organs, Immobilized enzyme reactors</td>
</tr>
<tr>
<td>Gina Shreve</td>
<td>PhD, University of Michigan, 1991</td>
<td>Environmental and biochemical applications, Microbiologically mediated biotransformations</td>
</tr>
<tr>
<td>Paul Van Tassel</td>
<td>PhD, University of Minnesota, 1993</td>
<td>Shape-selective catalysis, Protein adsorption and bioseparations</td>
</tr>
</tbody>
</table>

Matthew’s research involves tissue engineering and biomaterials and is working toward developing tissue- and organ-replacement systems. In one of his projects, he is investigating the use of polymer composites to fabricate small-diameter vascular grafts. The results are promising. Mao is working on surface templates made of molecules of mixed functional groups. She uses these molecular templates to induce and control the growth of dye crystals with tunable colors.

Among other things, Susil Putatunda is a cast iron expert. His research centers on several areas, including the development of high-carbon/high-silicon austempered steel, the fatigue and fracture behavior of austempered ductile cast iron, and the development of a fatigue-damage model for polymer-based composites.

Another of the department’s many active research groups, led by Yilun Huang, is studying intelligent process systems engineering and is developing a process synthesis methodology based on artificial intelligence and fuzzy logic. This work may lead to cost-effective, highly controllable and environmentally benign process systems. In addition, the research group hopes to meld optimal production with pollution prevention in electroplating plants.

With its staff of full-time faculty members, the department encompasses a diversity of research interests. While the faculty members take cues from local industry, they are very often much more than industry problem solvers; they are research innovators. They develop the new technologies that entice industry to come to them.

THE FACULTY

Faculty members new to WSU’s Department of Chemical Engineering and Materials Science are welcomed with substantial start-up funding and institutional support. They also find a firm advocate in the departmental chair. Once on board, faculty members continue to receive substantial internal support, including summer and graduate student support.

The department’s faculty team comprises fifteen full-time members, each of whom holds a national reputation in his or her specialty, and four adjunct professors who are affiliated with the graduate program. The faculty members have received many awards from prestigious engineering organizations and other institutions in the profession.

The faculty of the Wayne State Department of Chemical Engineering and Materials Science has many research options and educational possibilities open to them and their students. Being part of a major research university located in the heart of a metropolitan area, they are able to explore them all. ☐
Dear Editor:

In their recent article titled "An Experiment to Characterize a Consolidating Packed Bed" (CEE, 31(3), p. 192, 1997), Gerrard, Hackborn, and Glass misinterpret the Kozeny equation for low gas flow through packed beds and consequently arrive at an incorrect result.

The Kozeny equation as written by these authors is

\[ \Delta p = 5a^2(1 - \varepsilon)^2\mu hv / \varepsilon^3 \]  \hspace{1cm} (1)

(Nomenclature and numbering of equations follow those of the article criticized, with the addition that numbers assigned to corrected equations have the letter "a" appended to them.) In this form of the equation, the term \( a \) signifies the specific surface of the particles in the packed bed, i.e., particle surface area/particle volume, and is independent of the bed consolidation (assuming rigid particles). Therefore, in the authors' terminology,

\[ a = a_0 \]  \hspace{1cm} (3a)

The specific surface of the packed bed, particle surface area/bed volume, is given by the product \( a(1 - \varepsilon) \). Unfortunately, the authors incorrectly assume that a alone signifies the specific surface of the bed, and hence they write

\[ a = a_0 h_0 / h \]  \hspace{1cm} (3)

which is incorrect for \( a \) as used in Eq. (1).

If instead of Eq. (3), one correctly substitutes Eq. (3a) and the authors' Eq. (2),

\[ \varepsilon = 1 - (1 - \varepsilon_0)h_0 / h \]  \hspace{1cm} (2)

into Eq. (1), the result is

\[ \Delta p = 5a_0^2h_0^2(1 - \varepsilon_0)^2\mu hv^2 / \left(h - (1 - \varepsilon_0)h_0 \right)^3 \]  \hspace{1cm} (4a)

or

\[ \Delta p = kv^2h_0^2 / (h - G)^3 \]  \hspace{1cm} (5a)

where

\[ k = 5a_0^2h_0^2(1 - \varepsilon_0)^3 \mu \]  \hspace{1cm} (6a)

and

\[ G = (1 - \varepsilon_0)h_0 \]  \hspace{1cm} (7)

Rearranging Eq. (5a) gives

\[ \left(h^2v / \Delta p \right)^{1/3} = k^{-1/3}h - k^{-1/3}G \]  \hspace{1cm} (8a)

Thus it is \( \left(h^2v / \Delta p \right)^{1/3} \), and not \( (v / \Delta p)^{1/3} \), that should be plotted against \( h \) in order to linearize Eq. (5a). That approximate linearization was actually obtained by plotting \( (v / \Delta p)^{1/3} \) instead of \( \left(h^2v / \Delta p \right)^{1/3} \) against \( h \) can be attributed to the fact that the maximum decrease in \( h^{2/3} \) for the experiments performed was only 1 - (0.41/0.61)^{2/3} = 23%.

The authors should note that if they were to substitute their Eq. (9),

\[ a = 6(1 - \varepsilon) / D_p \]  \hspace{1cm} (9)

into Eq. (1), the right-hand side of the latter equation would then contain \( (1 - \varepsilon)^4 \) in the numerator, which is clearly incorrect. The error arises from the misinterpretation of \( a \), which is not the packed bed specific surface given by Eq. (9), but the particle specific surface given by

\[ a = \pi D_p^2 / (\pi / 6)D_p^3 = 6 / D_p \]  \hspace{1cm} (9a)

(Alternately, if we define \( a \) as the authors have done, then the \( (1 - \varepsilon)^2 \) term in Eq. (1) would disappear.)

Professor Norman Epstein

Department of Chemical Engineering

The University of British Columbia

Dear Professor Epstein:

Thank you for pointing out the correction, which makes the fit even better.

Professor Mark Gerrard

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**ChE Book Review**

**Batch Distillation Simulation, Optimal Design and Control**

by Urmila M. Diwakar

Published by Taylor & Francis, 1101 Vermont Ave., N.W., Suite 200, Washington, DC 20005; 211 pages including index; $59.95 (1995)

Reviewed by Phillip C. Wankat

Purdue University

Batch processes, and batch distillation in particular, are understudied in universities. The typical undergraduate separations textbook devotes a short chapter to batch distillation, and typical coverage in courses (CEER, 28, p 15, 1994) is from one to three class periods. The average graduate student does no additional study of batch distillation. Yet, batch distillation is an increasingly important separation method in industry, and there is significant interest in batch distillation research.

**Batch Distillation**, which is “primarily designed to serve as a textbook for a graduate course,” is very timely. The companion software MultiBatchDS (education edition from CACHE Corp.) was not available and is not reviewed here. A review of the book and the software from a consultant’s viewpoint was recently published (Chem. Engr. Progr., p. 77, June 1997).

If the software is available, this would be a good text for a graduate-level course. There are 38 homework problems in the book, which is probably sufficient for the first time the course is offered. With the exception that packed columns are not covered, the coverage is broad and most topics of interest are included.

Chapters 1 and 2 introduce batch distillation and analyze binary systems. These two chapters are a good resource for professors and undergraduate students, but some professio­nal guidance will be needed. For example, Eq. (1.6) and
CHEMICAL ENGINEERING AND THE OTHER HUMANITIES*

J.M. PRAUSNITZ
University of California • Berkeley, CA 94720

How is engineering related to other intellectual or professional disciplines? What is the role of chemical engineering in a modern university, and how does it fit into the spectrum of knowledge? And, finally, what can possible answers to these questions tell us concerning our educational philosophy and curriculum for training the engineers of the future?

These are difficult multidimensional questions with many aspects. I will discuss here only one aspect, one that is essential but has not received much attention: the need to remember that chemical engineering is not an isolated subject; that it is not limited to applied science, but rather is a significant part of daily life, related to health, to human relationships, to politics and sociology and law, to the way we think and feel about ourselves as individuals and as members of society, to our aspirations, our hopes, and our fears. In other words, I want to emphasize the old but too often forgotten concept that chemical engineering is not apart from, but indeed a part of, what (broadly speaking) we call the humanities.

Toward introducing that concept, Figure 1 shows a famous painting by Titian. The painting, about 400 years old, is in the Borghese Palace in Rome and is titled Sacred and Profane Love. Early in this century, a copy of the painting was on the wall of the seminar room of the Institute for Mathematics at the University of Göttingen in Germany. From the middle of the nineteenth century until 1933, when the Nazis started to destroy the German universities, Göttingen was the world’s leading center of mathematics, attracting the best minds of the day. In the seminar room, underneath the painting, was not the original title but a new one, Pure and Applied Mathematics.

We do not know who retitled Titian’s painting, but it was not only for amusement. The institute at Göttingen was far ahead of its time; not only was the mathematics done there new, vigorous, and bold, but (what was, and too often is still, unusual) the Institute also did outstanding work in both pure and applied mathematics. It was far ahead of other mathematics departments and gave serious attention to numerical methods for solving difficult differential and integral equations.

The painting and its new title were intended to stimulate discussion, starting with the obvious question: there are two female figures—which one represents pure mathematics and which one represents applied mathematics? The question can be argued either way. The woman without clothes could be identified with carnality, with the physical as opposed to the spiritual side of life, and therefore represents applied science, while the clothed, serious, brooding woman represents ascetic values, divorced from earthly concerns, and thereby represents pure science. On the other hand, we could argue that the absense of clothing and the upward ecstatic glance toward heaven represents purity, while clothing (notice that the clothes are coarse and drab) represents earthly values and that the clothed woman’s dour, downcast look represents the
chemical engineering is not an isolated subject; it is not limited to applied science, but rather is a significant part of daily life, related to health, to human relationships, to politics and sociology and law, to the way we think and feel about ourselves as individuals and as members of society, to our aspirations, our hopes, and our fears.

Titian’s painting shows that there is a unity in opposites, an old idea in philosophy: truth and ultimate reality are revealed to us in a variety of faces. In today’s world, we talk about unity in diversity, we read books about the increasingly similar roles of male and female, and we profess the virtues of blending Eastern and Western cultures. Sacred and Profane Love (or Pure and Applied Mathematics) illustrates the fuzziness, the growing disappearance of borders between intellectual categories. It shows what is increasingly recognized in universities today—that, while university departments may be necessary for efficient administration, intellectual concerns now overflow departmental division. Intellectual concepts are increasingly delocalized as the interests of faculty in one department overlap those in another.

My claim, that chemical engineering is one of the humanities, goes beyond the by-now clear evidence that contemporary chemical engineering is increasingly related to a variety of other physical and biological sciences. What is only slowly becoming apparent is that chemical engineering is also closely related to the social and humanistic “sciences,” where “sciences” is now in the original sense of “scientia”—that is, not necessarily natural science, but more generally, knowledge in all of its varieties. This close relationship follows from both practical and intellectual trends in contemporary society, as I shall now try to explain.

The practical trend is so fundamental that we are tempted to forget it: chemical engineers exist because society wants chemical products that will satisfy human needs. Chemical engineering is driven by society’s wish for a better life, where better is not only materialistic, but also deeply human—as for example, in medicine and pharmacy for health, in cosmetics for beauty, and in agricultural chemicals for feeding a hungry world.

I can best illustrate the practical and also deeply human basis of chemical engineering by recalling a revealing anecdote from a late colleague, Professor Irving Fatt, in Berkeley’s optometry department. He asked his class, “Who is responsible for the multi-million dollar contact lens industry?” As usual, initially there was silence, followed by some students shyly mentioning names of prominent polymer scientists. “Wrong,” replied Fatt, “The father—more correctly, the mother—of the contact lens industry was a poet, Dorothy Parker, author of the immortal lines, ‘Men seldom make passes...At girls who wear glasses.’”

My claim, that chemical engineering is one of the humanities, goes beyond the by-now clear evidence that contemporary chemical engineering is increasingly related to a variety of other physical and biological sciences. What is only slowly becoming apparent is that chemical engineering is also closely related to the social and humanistic “sciences,” where “sciences” is now in the original sense of “scientia”—that is, not necessarily natural science, but more generally, knowledge in all of its varieties. This close relationship follows from both practical and intellectual trends in contemporary society, as I shall now try to explain.

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derstanding of the ever-so-complex human soul, and that inevitably leads him to history, to psychology and to art—in short, to the humanities.

Both practical and intellectual trends in contemporary society make chemical engineering one of the humanities. The intellectual trend is not as evident as is the practical one, but it is clear to anyone who is familiar with what literature, art, and philosophy have emphasized for at least two generations: the dissolution of boundaries, the inter-relatedness of objects, phenomena, and observers. Nothing stands alone. Any one thing is without end, related to many other things. Literary critics tell us that to understand a text, we must probe not only into the author's history and his state of mind when he wrote his text, not only must we consider the customs and prevailing values that existed when the text was written, but we must also probe into the reader's history and his values and his state of mind when he reads the text. Thus, every interpretation depends on numerous factors, including the color of the book cover and the type of paper used by the printer. In the limit, this critique leads to the infamous movement "Deconstruction" where ultimately nothing objective remains. The only remaining ultimate reality is inter-relations.

The dissolution of boundaries is strikingly evident in art. Figure 2 shows Escher's *Night and Day*. Notice how the white birds flying to the right change, not abruptly but continuously, to black birds flying to the left.

The dissolution of boundaries extends not only in space, but also in time. Figure 3 shows a famous painting by Marcel Duchamp titled *Nude Descending Stairs* (An unsympathetic critic called this painting "Explosion in a Tile Factory."). We cannot localize the young woman; her fuzziness is not only spatial, but also temporal; she is simultaneously at the top of the stairs and at the bottom.

A related idea is indicated in a remarkably simple modern sculpture by my former graduate student, Dr. Bryan Rogers, who is now chair of the Art Department at Carnegie Mellon University. Bryan is probably the only person in the world who has a joint PhD in chemical engineering and in art. Figure 4 shows a set of clocks as found in any international airport. But the usual designations, e.g.,

![Figure 2. Night and Day, by Escher](image)

![Figure 3. Nude Descending Stairs, by Duchamp](image)

![Figure 4. Berkeley, by Rogers](image)
New York, London, Tokyo, Moscow, etc., have all been replaced by Berkeley. We see here the idea of inter-relatedness. No place is isolated; what happens anywhere in the world, happens also in Berkeley.

Twentieth-century philosophers like Heidegger, and especially his German disciple Georg Gadamer, and to some extent his American admirer Richard Rorty, have emphasized the importance of context and contingency. The significance and effectiveness of any object lies not in itself, but in how it interacts with its environment. This fundamental idea has greatly influenced recent and current work in history, literature, economics—in just about every social science and humanities department in every major university.

In literature, history, anthropology, sociology, law, business administration, etc., emphasis is increasingly placed on inter-relationships, on how one subject is related to another—in other words, on context. Historians of art are not only looking at what artists were doing at the time when a particular painting was created; they are also looking at the social relations that artists had with each other and their patrons, at the political climate of the time, at the literature of the day, at religious practices and conventions, and at the mechanisms artists used to publicize and market their work. Researchers in business administration are no longer primarily concerned with the internals of a corporation, but instead, with how the corporation relates to the community, with health and safety matters, with how corporations interact with other corporations, with government, and with social groups representing a variety of religions and ethnic traditions. Mathematical economists are interested not only in cash flow, taxes, and interest rates, but also in so-called externalities, including psychological factors, tastes, fads, fashions, perceptions, and the persistence and decay of myths and folklore.

No objects or subjects exist by themselves, but always in relation to other objects or subjects. Chemical engineering, by itself, has no value. The value and legitimacy of chemical engineering arise only when it stands in relation to something else, toward satisfying some human need, toward answering a question of deep human concern. Chemical engineering is an applied science in detail, but it is a humanity in intent.

[We must] show students how technology is related to human needs, both personal and collective; how applied science is a response to human aspirations and how it often is not just a consequence of, but also a stimulus to, pure science; and how the concerns of what men and women want and need drive the academic programs for all departments on campus.

Like everyone else at a scholarly institution, engineers or philologists, chemists or economists, physicians or theologians, we strive toward a better understanding of ourselves and toward a more noble life.

For chemical engineering education, the essential role of context should not be delegated to courses in humanities. To be truly effective, they can easily be integrated into the present chemical engineering curriculum. It takes only a little time to show students how chemical sciences relate to the world around us. Toward that end, the main requirement is an open-minded attitude by instructors, a willingness to depart from that confined area where they are expert and feel totally secure and to devote a few minutes to related areas where they are not expert but where the relevance of their subject lies and where they, as role models, can show humanity and openness to the world rather than the confinement of a narrow specialty. All too often the image that faculty present is such that only the instructors' expertise is visible, while their diverse talents, interests, passions, and weaknesses—in short, their humanity—remains hidden. No wonder that so many students think of faculty as a species separate from the rest of humankind!

The regrettable bifurcating mind of many faculty was aptly described in a short story by the Italian writer Ignazio Silone. In this story, the wife of a professor talks about him and gives the concise description, "Oh, he knows everything. But that's all he knows."

When we present the principles of refrigeration, we usually take a few minutes to discuss the desirable properties of refrigerants, including freons. At that time, it is a simple matter to talk briefly about how some freons attack the ozone layer that protects the earth from excessive ultraviolet radiation and to indicate the need for synthesizing new compounds that can serve as environmentally acceptable refrigerants.

To illustrate the principles of heat transfer, we need not confine attention to the time-worn double-pipe heat exchanger. Along with the usual equations for conduction, convection, and radiation, we could also talk about solar energy, cooling requirements for supercomputers, heat effects in reentry of space vehicles, cryosurgery, and such home-related topics as microwave ovens, fire-resistant pajamas for infants, or design of an effective fireplace.

When we talk about flowing fluids, let's mention check valves, rupture discs, human failures, and the tragedies at Bhopal in India and Chernobyl in the Ukraine. When we discuss condensers, let's mention fog at airports. When
we derive colligative properties of solutions, let's talk about salt for removing snow on our streets and then about subsequent corrosion of automobiles. When we discuss evaporation, let's mention desalting of sea water and the drought in Ethiopia.

When we encounter the free energy of formation of ammonia, let's also say something about fertilizers, about starvation in Somalia, and perhaps a few words about the latest farm bill passed by Congress. Further, let's recall for our students that ammonia is used for making nitric acid, that nitrates are used for making explosives, and that if Fritz Haber had not invented his synthetic-ammonia process early in this century, Germany would have run out of ammunition in 1915 and would have been unable to continue World War I after the first year.

I mention these examples not only to stress the relevance of chemical engineering, but also to suggest that, when taught with generosity, chemical sciences can serve as an integrating factor for understanding our living world as described in newspapers, television, and history books.

To prepare students properly for meeting the expanded expectations of society, faculty can no longer restrict their undergraduate courses to narrow specialization with the comfortable thought that the student's "other" educational needs will be supplied on the other side of the campus. The responsibility for good education cannot be so easily compartmentalized. There is a crucial difference between the words integrated and separate but equal, as the U.S. Supreme Court decided about forty-five years ago.

If we believe—and I suspect that we all do believe—that engineering is ultimately not merely a technical but also, essentially, a human enterprise, then we are obligated to communicate that belief to our students in a consistent way. We cannot meet that obligation by merely requiring our students to attend an occasional course in history or anthropology or whatever. If we are to be consistent in our purpose, then it is our task, in our own courses, to show the intimate continuity between applied science and ultimate human concerns.

Pressures from government and its funding agencies are already providing incentives to encourage teamwork in research, better cooperation with industry, team teaching, interdisciplinary courses, and lowering of departmental barriers—in short, toward integrating engineering education and research with those broad areas that engineering serves. Funding agencies now prefer research proposals that are problem-oriented, to be conducted not by separate investigators but by a team of scholars from several disciplines. At the same time, students and parents are demanding that more attention be given to courses that emphasize "why" instead of "how," that stress overall purpose rather than details of method, and, as a perceptive undergraduate at the University of Rochester said, "to courses that give fewer scales and more music."

As it prepares for the next century, every chemical engineering department faces two challenges. The first one is well known and relatively simple: to keep up with impressive new developments in science and to make them relevant for practice. Surely that is one of the traditional goals of engineering. It is likely that essentially all chemical engineering departments will meet this first challenge with success.

The second, and more difficult, challenge is to humanize the curriculum, not through new courses but by introducing into existing technical courses the human dimension; to show students how technology is related to human needs, both personal and collective; how applied science is a response to human aspirations and how it often is not just a consequence of, but also a stimulus to, pure science; and how the concerns of what men and women want and need drive the academic programs for all departments on campus. Like everyone else at a scholarly institution, engineers or philologists, chemists or economists, physicians or theologians, we strive toward a better understanding of ourselves and toward a more noble life. In our relations with students and faculty in other departments, let us not be separated by our differences but joined by our common purpose.

I plead for teaching this commonality of purpose not only because it is fashionable to reverse the alarming trend of the university to a multiversity. My plea is motivated by two equally important goals.

Figure 5.
I and My Village, by Chagall

Chemical Engineering Education
First, if we humanize our curriculum, we produce better engineers, we raise the prestige of engineering, and we help to combat the threatening anti-science and anti-technology movements that are growing in our alienated population. Engineers must increasingly communicate, to listen with empathy to those who do not understand or who are frightened by new technology, and to speak to them effectively, leading them toward confidence and trust. Good skills in English are not enough. The engineer must also have some understanding of his audience; in other words, he needs to understand the human dimensions of his work. In the world now emerging, an American engineer must know how to communicate, to listen and to speak, with a peasant in India, a rabbi in Jerusalem, or a lawyer in Washington.

Second, a chemical engineering department is not a trade school. A worthy chemical engineering department is not content to limit its educational efforts toward producing robots for industrial employment; it strives to produce thoughtful, sensitive, and independent-minded graduates who are not only competent engineers but also well-educated individuals, prepared for fulfilling lives both inside and outside their profession. To achieve this educational goal, engineering faculties must integrate and interrelate what we do in engineering with the greater world that engineering aims to serve.

Toward explaining my conviction that engineering is an integral part of our spiritual as well as our physical existence, I have shown examples from several artists. Finally, I would like to show one more: a well-known painting by Marc Chagall, painted about seventy-five years ago when Chagall was a young man remembering his childhood in rural Russia. In a sense, it is an autobiography. It is called *I and My Village* (Figure 5), and it indicates the influences that made Chagall the particular individual that he was at that time. It shows a set of memories that are separate, yet integrated to form a harmonious continuum.

Contrast this painting with the essential image we use to teach applied mechanics—the free-body diagram. In a free-body diagram, we isolate the essentials of our focus of study, we neglect the surroundings, and we ignore the context.

In teaching chemical engineering, we also use free-body diagrams. For example, as shown in Figure 6, in teaching distillation we look at one plate in the distillation column and then write mass balances for all flows that enter or leave that plate. In this exercise we forget not only the rest of the distillation column but also the entire chemical plant and the community that it serves.

I am not opposed to free-body diagrams, nor do I suggest that we refrain from using them in instruction. Free-body diagrams constitute a pedagogical tool that has been, and continues to be, valuable for effective education. But free-body diagrams convey an attitude, a philosophical viewpoint that is seriously incomplete. We should not abandon free-body diagrams, but we should not restrict engineering education to the attitude that they imply. I plead for a shift of balance where we rely not only on the isolated specifics but also, as suggested by Chagall’s painting, give attention to the larger view, toward awakening engineering students to see both the leaves on the trees and the forest, the mountains and the cities, and the human beings that live in them.

To illustrate this shift of balance, to help our students broaden their professional horizons and to attain more meaningful lives, it may be useful to recall a well-known (possibly true) story concerning the great physicist Niels Bohr.

Bohr, a distinguished professor of physics at the University of Copenhagen, liked, on occasion, to retreat to a modest cabin in a nearby forest where he could read and think without interruption. But an enterprising journalist discovered this cabin, and wanting to interview Bohr, knocked on the door. Bohr opened the door and the journalist entered. When he did so, he noticed an old horseshoe nailed to the door frame. Surprised, he said to Bohr, “You are a great scientist. Surely you are not superstitious. Surely you do not believe that a horseshoe can bring good luck.” Bohr answered without hesitation, “Of course I do not believe that. But I have been told that a horseshoe can bring good luck even if you don’t believe it.”

This charming story tells us once again that, even for a great scientist, life has a strong non-rational component and that we are all human beings subject to the hopes and fears that characterize the human condition. Let us reflect this duality when we teach our students science and technology. Let us not rely on others to do what we owe to the young men and women entrusted to our care. Let us show by our example and in our classrooms, that engineering, in particular chemical engineering, is also one of the humanities.
COMET
An Open-Ended, Hands-On Project for ChE Sophomores

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Sophomore chemical engineers at Georgia Tech recently built Controlled-Operation Mechanical Energy Transducers (COMETs) as part of a project to introduce them to a number of important engineering concepts that are often not addressed until later in the curriculum, if at all. In the COMET competition, student teams designed, built, and used simple, self-powered devices that independently traveled to a designated location.

While electrical and mechanical engineering students frequently participate in design competitions involving student-built machines, chemical engineering students’ hands-on experience is usually limited to prefabricated laboratory experiments during the junior or senior year. To introduce activities other than pencil-and-paper homework assignments earlier in the curriculum, development of hands-on design projects appropriate for beginning chemical engineers has recently received increased attention. Motivated by this concern, I developed and offered the COMET competition in two consecutive sophomore-level classes on energy balances. It was designed to achieve the following goals:

• **Teamwork** Students formed teams of two to four members who worked together on all aspects of the projects.

• **Open-Ended Problem** Because there were few rules in the competition, many possible designs could accomplish the assignment.

• **Design** Given only a spending limit and a final goal, students had to design, build, test, and use their COMET.

Figure 1. Schematic of the COMET competition arena located on an indoor basketball court. COMETs traveled by land and/or air from a launching area, around or over a large barrier, and to as close to a target location as possible. The COMETs were designed and built by teams of sophomore chemical engineers.

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*Excerpt from a final COMET report written by a team of students.*

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Chemical Engineering Education
- **Hands-On Experimentation** Because a successful COMET design depended largely on empirical physical testing, students needed to get their hands dirty.

- **Technical Writing** Each group prepared a final report that described and analyzed the design of their COMET, including written text, figures, and calculations.

- **Estimation Based on Limited Data** Quantitative estimates of kinetic and potential energies were required in the final report. Students designed and performed additional experiments to calculate rough estimates of those energies.

### THE ASSIGNMENT

The COMET project had few rules, thereby giving students the opportunity for creative design. In groups of two to four students, each team designed and built a COMET that could be launched from a designated location and, without human intervention after launching, would come to a stop as close as possible to a target location approximately forty feet away (Figure 1). To make the assignment more challenging, a large object was placed five feet in front of the target so that a straight path to the target would be blocked. The COMET had to cost less than $20, measure less than one foot in all dimensions, have no electrical, chemical, or human power sources, and be safe. The COMET could have a separate launching unit of any size, but the launching unit had to remain behind the starting line.

The assignment was given to the students two to three weeks before the competition. Immediately before the assignment was given, we held an in-class brainstorming session to help students think broadly about the project. We identified possible paths an object could follow between two points separated by a barrier and considered ways in which an object could be powered to follow some of those paths.

One week before the competition, a preliminary design of the proposed COMET and its expected course was collected to ensure that each group had started work on the project. I provided feedback on these preliminary designs, commenting on approaches that seemed overly complex, unlikely to work, or unsafe. Students also received sample energy balance calculations to guide them in preparing their reports, as described below. Optional practice sessions were held before the competition so that teams could test their COMETs in the competition arena.

### THE COMET COMPETITION

The competition consisted of three rounds. During each round, each team in turn launched its COMET toward the target (see Figure 2). The referees *(i.e., class TAs)* measured the shortest distance between the target and the COMET.

Figure 2. COMETS being launched at the competition.

(A) The “Tomato” team shot a rice-filled balloon from a rubber band-powered cannon.

(B) The “Quadrangular” team COMET drove to the side of the barrier and then made a 90° turn by triggering a second set of wheels.

(C) The “Slingers” launched a putty-based COMET from a slingshot.

(D) The “Spartans” vehicle followed an arced path around the barrier and was powered in part by a rat trap.
After the third round, the teams were ranked by aggregate score from all rounds of play. Members of the winning team each received a small trophy.

The ability of the COMETs to reach their target ranged from reproducibly having no net movement to reproducibly landing and stopping within inches of the target. Most designs were based on potential energy stored in the form of a spring or rubber band that was used to catapult an object through the air. Others used the potential energy of gravity to move the COMET either on the ground, through the air, or a combination of both.

Designs ranged from store-purchased projectiles modified for the competition to homemade vehicles, some with complex and clever mechanisms to control the COMET’s direction and speed. While the complex designs were fun to see, they were generally unreliable and yielded only average performance. The winning designs in both of the COMET competitions were either a rocket or an arrow launched from the ground at a predetermined angle with a reproducibly applied force and having a mechanism to prevent rolling or bouncing once the COMET hit the ground.

THE FINAL REPORT

Although the competition was the highlight of the COMET project, grades were determined from each team’s final report. The report was due two days after the competition and consisted of four parts:

1. A schematic diagram and description of the COMET
2. A sketch and description of the intended course the COMET would follow
3. Receipts for items used to build the COMET
4. Quantitative energy-balance calculations for each phase of the COMET’s travel

Grading was based half on clear, concise, and neat presentation and half on energy balance calculations. Quality of COMET design and construction and the COMET’s ability to reach the target did not influence grades as long as each team had made a reasonable effort to do well.

The final reports were generally clear and well written, and they provided reasonable analysis of the energy balances associated with the COMET’s travel. The sketches of the COMET design and its intended course were mostly simple, hand-drawn diagrams (see Figure 3) supported by one or two paragraphs of descriptive text. The receipts all totaled under $20, as required in the assignment; some amounted to just a few dollars.

Students performed energy balance calculations for each phase of the COMET’s travel. A representative example follows, taken from the “Bernoulli Bunch” group’s analysis of a COMET that was shot into the air from a rubber-band sling shot, landed on the ground, and finally bounced and rolled to a stop. First, these students estimated the elastic potential energy of the rubber band equal to the gravitational potential energy gained by the object. They determined this energy to be 1.4 J. They then calculated the COMET’s velocity to be 11 m/s upon leaving the rubber-band launcher by setting the COMET’s kinetic energy equal to the potential energy lost by the rubber band.

Using energy balances applied when the COMET reached its maximum height, first hit the ground, and finally stopped, they determined at each point the COMET’s kinetic and potential energy, as well as its position and velocity.

ASSESSMENT OF THE PROJECT

From the instructor’s perspective, the COMET project accomplished the six goals for which it was designed. Students responded well to the teamwork environment and seemed to share group responsibilities. They also approached this open-ended design project with an open-minded attitude, as demonstrated by the many different types of COMETs built, most of which worked well. Students spent a lot of time building and testing their COMETs, which indicated they enjoyed the opportunity for hands-on learning. The final reports contained adequate technical writing and data analysis, topics that are addressed more thoroughly in later classes.

To assess student opinion of the project, a brief, anonymous survey was given a week after the assignment. It revealed that students generally found the COMET project to be educational, enjoyable, and worth repeating. Figure 4 shows student responses to the three specific questions asked. Students also provided written comments, which are summarized below.

The average scores shown in Figure 4 indicate generally favorable responses by the students, but not enthusiastic endorsement of the project. This observation should be tempered in two ways. First, a large standard deviation is associated with each average, largely due to a few students who...
Figure 3. A sample student sketch of the intended course the COMET would follow to the target (above) and a schematic diagram of the COMET launching unit (below) from the "COMET Busters" team final report.

Figure 4. Student assessment of the COMET project. Based on anonymous responses from 28 students (solid bar) and 34 students (grey bar) in two different classes, averages and standard deviations are shown for responses to the following: Rate your learning from the COMET project (1 “waste of time” to 5 “very valuable”); Rate your enjoyment of the COMET project (1 “dull” to 5 “lots of fun”); Give your recommendation on using the COMET project again (1 “absolutely not” to 5 “absolutely yes”). Overall, students found the COMET project to be educational, enjoyable, and worth repeating (see text).

were unhappy with the project and rated it with a 1 or 2. The vast majority of students gave ratings of 3 and higher on all three questions. If the averages were recalculated without the two or three dissatisfied students in each class, all three questions would have average values above 4. Second, the scores from the first class were consistently higher than scores from the second class. Based on student comments, this difference is largely due to greater time pressure: the second class received only two weeks to work on the project, while the first class received three weeks.

Some representative student comments are provided below, followed by a discussion of what these comments say about the successes and shortcomings of the COMET project.

Enjoyable Project

"This is the only project I have had at Tech that was enjoyable. I didn’t even feel like I was doing a project for a grade."

"Fun project, but still learned a lot."

Many students enjoyed the project. They were surprised to find that something educational could also be fun. Making the connection between academic values (i.e., learning) and personal values (i.e., fun) may be the most important lesson of the project. Student-perceived relevance of course material is known to be important for effective learning.[7,8]

Hands-On Learning

"It was nice to do something in ChE away from paper and theory."

"Home Depot is very fond of Georgia Tech students."

A number of students commented on the hands-on nature of the project and appreciated it as a refreshing change from conventional problem sets. The opportunity to exercise “right-brain” thinking through an active process that yields concrete results appeals to students with learning styles not easily accommodated in conventional “left-brain” classroom lectures.[9]

Weak Connection with Course Material

"I don’t think I really learned anything from the project that pertained to the course."

"I’d suggest allowing chemical energy sources. After all, this is a Chem E class."

Some students were concerned that the project was not closely related to the rest of the course material. I partially share this concern. While the quantitative energy balance calculations required in the final report relate directly to material presented in lectures, the design, construction, and testing of COMETs are not as closely linked to the rest of the course. Nevertheless, I believe it is important to expose engineering students to concepts like teamwork, open-ended design problems, and hands-on experimentation, and I think the COMET competition provided an exciting framework

Continued on page 45.
Educational researchers have identified a need to expand the typical teaching approach found in most engineering courses beyond the lecture and problem-set format. Strict adherence to this traditional teaching method has several shortcomings. First, students possess a variety of learning styles. Educational researchers have attempted to correlate learning styles with traits such as Meyers-Briggs Type Indicators, gender, and regions where the students grew up. By implementing only one teaching method, educators can lose some of their audience and place some students at a disadvantage. Second, traditional teaching methods often do not promote the creativity desired by most employers and researchers. Third, traditional methods of teaching do not necessarily encourage students to develop the self-reliance essential in an industrial job or in graduate research. In the "real world," problems do not come out of a book, numbered and self-contained, nor do they proceed directly from the previous day's lecture. Ultimately, graduates need to be able to define their own problems and to determine what information is needed to solve them. Finally, engineering problems sets do not emphasize the importance of communication.

In this paper, we present an open-ended project tailored for a senior kinetics and reactor design course. The project is based on work by Penry and Jumars in which basic reactor design equations are used to model the digestive system of several animals. We will begin by describing the assignment, will follow with the results, and will close with some overall conclusions about the success of such a project.

THE ASSIGNMENT

We asked the students to model the digestive system of an animal of choice as one or more ideal reactors, applying principles from the course. There are three aspects of the project, each with its own goal: a literature search, the development of a model, and the communication of the model to an audience. While the project is intended to be open-ended, students in general do not respond well to nebulous assignments so we gave them our concrete expectations at the very beginning, including specific goals to attain for each aspect of the project.

We asked each student to choose his or her own individual animal, thus ensuring that each model would be unique. Individual choice also allowed the students to apply the project to an animal they found personally interesting.

The first phase of the project focused on searching the literature. To build a theoretical model of their animal's digestive system, students had to acquire information about the diet (reactant feed), the digestive process, gut size (reactor volumes), throughputs, and any enzymatic and bacteriological kinetic rate data from the literature. Not surprisingly, there is an abundance of literature information of some animals, but very limited information on others. We recognized that some students would find this disparity frustrating.
In this paper, we present an open-ended project tailored for a senior kinetics and reactor design course. The project is based on work by Penry and Jumars in which basic reactor design equations are used to model the digestive system of several animals.

### TABLE 1
Digestive Schemes

Animals display a variety of digestive schemes to handle available food sources. Single reactor schemes can model simple animals with minimal energy requirements, like starfish. Larger animals with higher energy requirements offer a larger variety of digestive schemes. Carnivores, frugivorous primates, and omnivorous humans all possess a simple stomach and small intestine to break down high-energy food.

Some animals rely on more readily available, lower-energy foods such as grasses and leaves. These animals generally need the assistance of microbes to break down food to provide energy. **Foregut Fermenters** are animals in which microbial fermentation of ingested material precedes catalytic digestion (e.g., cows, sheep, goats, deer, hippos, kangaroos, whales, and manatees). Microbial fermentation takes place in a well-mixed rumen or complex stomach, after which the food passes to a long, tube-like intestine where catalytic digestion occurs.

**Hindgut Fermenters** (e.g., horses, rhinos, koalas, rabbits, and elephants), microbial fermentation takes place in the cecum following catalytic digestion.

The next phase of the project was model development. We asked the students to sketch the ideal reactor series employed and to present the equations used to predict conversions and residence times. This portion of the project allowed students to apply course knowledge to a new problem that they devised for themselves. Based on their literature search, they had to decide what reactor or reactor series was appropriate, where there was essentially continuous flow, whether mixing was ideal, and what reactions were important. If experimental data were available in the literature, model predictions were to be compared with experimental values of conversions and residence times. Generally, kinetic and conversion data are not available for most animal species, so students were asked to fill in the gaps with appropriate assumptions by extrapolating data from other related species. In cases where such extrapolation was not feasible, students were asked to describe in detail how one might experimentally gather kinetic data on the digestive system to compare with their model.

Along with the model, students were asked to provide a critique, discussing the strengths and weaknesses of their analysis, and to describe how well it would serve to predict reality. The critique forced the students to think about the equations and to understand the assumptions that go into them at a high enough level to be able to explain it to others.

The last aspect of the project was the development of communication skills. In addition to the short summaries of the literature articles, students had to prepare a written report describing the model of their animal’s digestive system, including an introduction motivating the application of the model to their animal. A small class size also allowed the students to make oral presentations of their report. The emphasis of the oral and written reports was on organizing a coherent presentation of the model, its motivation, and its critique.

**GUT MODEL DEVELOPMENT**

As stated in the introduction, this project is based on Penry and Jumars’ work using basic reactor design equations to model the digestive system of a variety of animals and to identify the digestive operating systems that optimize the utilization of nutrients and the production rate of energy. Their reactor design models and basic kinetic rate expressions can be found in most undergraduate kinetics and reactor design textbooks, making the development ideal for...
use in the classroom. The authors discuss modeling the guts of marine deposit feeders, mammalian hindgut fermenters, and mammalian foregut fermenters (see Table 1).

In their analysis, the authors assume that digestive reactions are homogeneous, kinetically controlled enzyme processes in which food component A binds reversibly to enzyme E and dissociates irreversibly into product(s) P and free enzyme:

\[ A + E \leftrightarrow EA \rightarrow P + E \]  

They further assume that all digestive reactions fall into two main categories. Digestive reactions catalyzed by an animal’s own enzymes are described by the Michaelis-Menton kinetics and follow the rate expression

\[ -r_A = \frac{v_{\text{max}} C_A}{K_M + C_A} \]  

where

- \( C_A \): concentration of A
- \( v_{\text{max}} \): \( \frac{k_c}{k_c + k_c} \)
- \( K_M \): \( \frac{k_c}{k_c + k_c} \)

Digestive reactions that rely on microbial fermentation are autocatalytic. Microbes M are produced as food component A is broken down. This can be described by

\[ A + M \leftrightarrow MA \rightarrow P + M + M \]  

Such reactions have an additional dependence on the concentration of microbes, \( C_M \):

\[ -r_A = \frac{v_{\text{max}} C_A C_M}{K_M + C_A} \]  

Reactor design texts\(^{[9-12]}\) derive design equations for the three ideal reactors used in the gut analysis of Penry and Jumars: batch reactors, plug flow reactors (PFRs), and continuously stirred tank reactors (CSTRs). The time in a batch reactor or space time \( \tau = \frac{\nu}{\nu} \) in a continuous flow reactor required for digestion to achieve a particular conversion, \( X \), can be found using the familiar design equations

\[ \tau = N_{A0} \int_{0}^{X_{\text{final}}} \frac{dX}{-r_A} \] (5)

\[ \tau = \frac{V}{\nu} = C_{A0} \int_{X_{\text{in}}}^{X_{\text{out}}} \frac{dX}{-r_A} \] (6)

\[ \tau = \frac{V}{\nu} = \frac{C_{A0}(X_{\text{out}} - X_{\text{in}})}{(-r_A)_{\text{out}}} \] (7)

where

- \(-r_A\): reaction rate
- \( N_{A0}\): initial number of moles of reactant A
- \( C_{A0}\): feed concentration of A
- \( V\): reactor volume
- \( \nu\): volumetric flow rate of the feed

Figure 1 shows the graphical design equation for finding the space time of an animal gut performing a catalytic digestion process following Michaelis-Menton kinetics. To minimize the space time, Michaelis-Menton catalytic digestion is optimized by a PFR design. Figure 2 shows a plot of reciprocal reaction rate versus conversion for an autocatalytic microbial fermentation process. Autocatalytic reactions are optimized by a CSTR operating at the point of maximum reaction rate, followed by a PFR.

Penry and Jumars suggest general designs for deposit feeders, mammalian hindgut fermenters, and mammalian foregut fermenters. Depending on the specific animal being modeled, reactor design models may need modifications to account for various factors—such as variable flow rate, variable gut volume, non-ideal mixing, recycling by means of coprophagy (reingestion of feces), and caecotrophy (reingestion of partially separated feces, as in rabbits)—and residence time distributions. Modifications to the reaction kinetics may account for different forms of enzyme kinetics, mass-transport limitations, heterogeneous catalysis, and non-isothermal conditions. Ultimately, fundamental reactor de-
sign equations can form a biologically meaningful, mathematical framework for the description of animal digestion.

**STUDENT ANIMAL GUT MODELS**

Using the tools of kinetics and reactor design and the ideas presented in the work of Penry and Jumars, the class was able to develop models about the digestive behavior of animals across the animal kingdom. Some animals had seemingly simple digestive systems, while others had more complex guts. Table 2 lists typical animals that students modeled. A few of the animals were modeled with single ideal reactors (vampire bat, sea anemone, starfish) and offered simple systems like the deposit feeders in the article by Penry and Jumars. Many of the animals required a series of reactors. A student model of the hippo gut (foregut fermenter; CSTR-PFR) is presented below. Several students extended their model to account for digestive behavior distinctive to their animal, using either additional reactors or modification of the underlying assumptions. Two prime examples are also presented below: a koala bear (hindgut fermenter; CSTR-PFR-Sepinator-CSTR-PFR) and a manatee (hindgut fermenter; CSTR-PFR-CSTR-PFR).

**Hippopotamus**  
Hippopotamuses are foregut fermenters that spend about five hours a day eating about 40 kg of short grasses. The student modeled hippo digestion with a CSTR and a PFR in series with information about the volume of the stomach, the length of the intestines, and the feeding rate from the literature. The model is shown in Figure 3.

The volume of the intestine was calculated based on data of the distribution of digesta between the stomach and the intestines. Reactor volumes and throughputs allowed for the estimation of fairly reasonable residence times: $\tau_{\text{CSTR}} = 3.5$ days, $\tau_{\text{PFR}} = 1.1$ days. The student suggested tracer studies to check the accuracy of these estimates. Detailed kinetic data were not available to calculate the actual conversions. The student discussed how one might get the kinetic information experimentally, either by monitoring hippos in the field, examining hippo excrement, or by extrapolating from a known body of data on animals with similar digestive systems (e.g., cows). Researchers could then use the design equations and compare calculated conversions with those found experimentally. Because the nightly feeding of hippos only lasts about five hours, a more rigorous model would account for the unsteady nature of the digestion process.

**Koala**  
Koalas are hindgut fermenters with a unique diet. Exceptionally picky eaters, koalas focus entirely on a select, low-quality food source—eucalyptus leaves from only about 5 of over 100 available species. Koalas have evolved highly specific guts to digest this food source, and reactor design analysis can give insight into the importance of nature’s design.

The contents of eucalyptus cells are highly digestive, according to the literature. The student assumed that all digestion of the cell contents occurred in the stomach and small intestine by means of catalytic digestion. Microbial breakdown of the eucalyptus cell wall occurs only in the cecum and the colon. Koalas are not born with these helpful microbes, but rather gain them from ingesting adult fecal matter shortly after being weaned.

The model of koala digestion is shown in Figure 4.

* On a field trip to the San Francisco Zoo, the class learned of the availability of hippo excrement; hippos leave the water to distribute their feces rather widely to mark their territory.

** On the same field trip to the San Francisco Zoo, we learned of weaning and eating habits of young koalas.
Literature provided the student with tracer and dissection studies of koalas that reveal two main residence times in the koalas' guts. The mean residence time for particulate matter was about 100 hours, while that for the solute phase was about 210 hours. The student decided to employ a separation process within his model to account for these two residence times. Because koala eating is spread fairly continuously throughout the day between periods of sleep, the student modeled koala digestion as a continuous process.

Using this model and literature values for throughput rate and gut volumes, the student was able to match the experimental residence times for both the coarse particles and soluble fine particles. Unfortunately, the student was unable to find kinetic data for these reactions; he pointed out that kinetic data would allow one to study the digestion of koalas with mathematical models and reduce the need for slaughter/dissection studies.

**Manatee** • Another modification of Penry and Jumars' hindgut fermenter was presented by a student who modeled the guts of manatees. A scheme of four reactors was chosen to model its digestive behavior. The student decided that Penry and Jumars' model of a hindgut fermenter PFR-CSTR series was a poor choice in the case of the manatee for two main reasons: first, manatees are known to achieve large conversions, and large conversions that operate beyond the maximum autocatalytic reaction rate are inefficient in a CSTR, and second, the long curvaceous nature of the colon, coupled with the viscous nature of the digesta found in the manatee makes perfect mixing unlikely.

Like horses and elephants, manatees use the cecum and colon as primary fermentation sites, whereas the stomach and the small intestine are used for catalytic digestion. Because both the colon and the small intestine are long and narrow, they were both modeled as PFRs. The open cavities of the stomach and the cecum are more amenable to CSTR design. Thus, a CSTR-PFR-CSTR-PFR series was chosen to model the manatee gut, as shown in Figure 5.

Equations of forms (2) and (3) were used to model the catalytic digestion and the autocatalytic fermentation reactions, respectively. CSTR and PFR behavior were modeled using Equations (5) and (6). The student was unable to find kinetic data specific to manatees, but she was able to find the typical range of rate parameters \( V_{MAX} \) and \( KM \) found in hindgut fermenters for fermentation and catalytic digestion processes. The only unknown variable is \( C_m \), the concentration of microbes. For the purposes of calculating general trends, the student assumed that the microbe concentration was directly related to the concentration of food, \( C_A \). Now, by examining each reactor in sequence, one can calculate the output \( C_A \) and conversion.

Even with her broad kinetic generalizations, the student found that the theoretical overall conversion fell between 60% and 80%, comparing extremely well to the literature, which cites 45% to 70% for manatees (and about 84% for dugongs, another species of sea cow).

As weaknesses of her model, the student cited several factors, including the lack of true kinetic data, the assumptions of constant volume digesta, and complete mixing in the CSTR compartments. This model allows one to conceptualize the conversion of food, however, and illustrates the efficiency of nature in designing its own reactors.

**ANIMAL GUT DESIGN AS A TEACHING TOOL**

Students (and instructors) responded well to this open-ended project. It was enjoyable for everyone and it added a unique dimension to the class. As a teaching tool, the project was a success on several levels. While the subjective nature of evaluating student performance makes it difficult to give direct, quantitative comparisons with more traditional problem assignments, there were several indicators by which we were able to judge this project's success.

Foremost, it was obvious that students learned from this exercise. The project allowed students to apply kinetics and reactor design concepts and to extend their knowledge of course material to a unique reactor system. Based on their own knowledge, they had to decide for themselves what model assumptions were appropriate. The project saw the development of several fairly comprehensive models built to account for complex reactive and flow behavior. The in-class presentations allowed students to present to and teach each other about the applicability of ideal reactor models.

Not only was the project instructive, but it was also enjoyable to the students. Overall, student response was highly positive.
favorable. When asked their opinion of the course afterwards, students responded that they “enjoyed the project” and that it was “fun”—phrases rarely used to describe a typical homework set.

We did receive a few less positive responses at the beginning of the project. While some students liked the flexible nature of the project, a few students worried about what was meant by “the project’s success being up to them.” Several students were initially turned-off by the idea of an open-ended literature search. We dealt with complaints about trying to chase down details that may or may not exist in a large body of literature in a case-by-case manner. Ultimately, the students developed searching strategies and were able to organize the information. The open-endedness of the project made creativity possible, which the students all seemed to enjoy.

An additional success indicator was increased office hour attendance. Students who previously had not shown excessive interest in course material began arriving early and asking questions. Several became quite stimulated by the topic and would engage each other in discussion about their models. These discussions provided an effective cooperative learning environment in which students relied on each other to learn and to teach the subject matter.[1]

Finally, students were both more creative in their problem solving and more expressive in the discussions of their models. This project was a success as a teaching tool because its open-endedness and active learning emphasis appealed to a wide variety of learning styles. The open-ended project was complimentary to more traditional problem sets in that it allowed students to extend their knowledge beyond what had been directly presented in the classroom.

CONCLUSIONS

Reactor design models can be successfully employed to model the guts of a variety of animals, and the use of such models on unique animal systems provides a stimulating learning experience for both the students and the instructor. We would encourage any one teaching a reactor design class to use this or a similar type of project to engage the students and help seize their interest.

ACKNOWLEDGMENTS

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REFERENCES


INTRODUCTION TO THEORETICAL AND COMPUTATIONAL FLUID DYNAMICS

by C. Pozrikidis

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Reviewed by
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Introduction to Theoretical and Computational Fluid Dynamics is an ambitious text, attempting and largely succeeding to encyclopedically cover the theoretical fundamentals of incompressible, nonturbulent Newtonian fluid mechanics. In addition, the book gives a flavor of the numerical methods by which fluid dynamics problems are often solved. The

Continued on page 75.
The papers in this series* stalk the question of what we mean by an understanding of technical material. We have asserted that to understand has multiple meanings, and we organized those meanings into a hierarchy of seven levels: (1) Making conversation; (2) Identifying elements; (3) Recognizing patterns; (4) Solving problems; (5) Posing problems; (6) Making connections; (7) Creating extensions. In the second paper of this series, we discussed understanding at Levels 1 through 4, which we refer to as elementary understandings. To progress beyond problem solving at Level 4, we must realize that solving a problem is not the same as knowing how to solve it. This realization marks the beginning of the transition to the more advanced levels addressed in this paper. The discussions here rely on the descriptions of brain structure and function that were summarized in the first paper of the series.

Transition:

Level 4 (Solving Problems) to Level 5 (Posing Problems)

Motivation: Solving a problem is not the same as knowing how to solve the problem.

Reformulation: The initial solution procedure is refined by rehearsal and the problem plus its solution are explored by exercising variations on a theme.

LEVEL 5: POSING PROBLEMS

We practice problem solving not to obtain an answer, but to learn how to solve problems. That is, implementing a procedure to obtain an answer occupies a lower level of understanding than does devising the procedure. To develop skills for solving problems, we must confront new problems, solve them, and then solve them again and again. Repetition allows us to shift our attention from obtaining an answer to learning a procedure. Repetition also promotes creation of long-term memories, which we need for reusing a procedure in the future. The connections between repetition and memory will be discussed first, then we will make connections between repetition and problem solving.

Posing Problems to Create Memories

Creating memories serves as one hedge against future needs. In particular, long-term memories (certain long-lasting neural networks and combinations of networks) enable us to reuse problem-solving strategies that we have found successful in the past. At the subconscious level, we don’t know how the brain selects what ideas are to be remembered. That is, in spite of popular wisdom, the brain does not lay down a memory for every mental state nor for every sensory experience; on the contrary, most pass through short-term memory and are lost. But we do know that we can consciously select what ideas are to be remembered and we can consciously create those desired memories; the operative mechanism is repetition—repeatedly thinking about the ideas.

Repetition causes the cortex to repeatedly fire the same pattern of neurons; such repeated activations appear to strengthen synaptic junctions and perhaps develop new junctions. Thus, by repeated use, a track through a wilderness becomes a path, then a walk, and finally a highway. Moreover, besides strengthening connections, repetition also seems to refine the neural network that reproduces the desired

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* Part 1, “Brain Structure and Function” was published in the summer 1997 issue of CEE (Vol. 31, No. 3) and Part 2, “Elementary Levels,” appeared in the fall 1997 issue (Vol. 31, No. 4).
firing patterns—it makes the network more efficient. When
the mind contrives a pattern for a new idea, it seems to arise
“on the fly”—the new thought is hastily thrown up as a
permutation of an existing pattern. If a new idea seems
interesting or important, and therefore worth remembering,
then repeatedly thinking about it may create
a new network that is largely separated from the
parent network but connected to other
networks that represent related ideas.

Perhaps a helpful metaphor here would be
scaffolding. A new, hastily constructed, network is a fragile thing, momentarily stabilize
by a scaffolding of neural connections
that allow us to examine the new idea. If the
idea is judged worthy, then we use repetition
to strengthen important synaptic junctions in
the network and remove the scaffolding. Often,
the scaffolding is produced by studying
the intermediate details that appear in any
logical development, such as those that connect
a conclusion to a hypothesis, those that relate an effect to a cause, and those that connect an answer to a problem statement. Without intermediate details, scaffolding is sparse or nonexistent, and student understanding remain poorly developed. Repetitions make such connections at first plausible, then acceptable, and finally obvious—these correspond to stages in removing the scaffolding.

Repetition also serves to distinguish procedural memories from episodic memories. Procedural memories are created by conscious practice, while episodic memories are apparently created from a single experience. How might episodic memories be formed? Deep in the brain, forming part of the limbic system, is the hippocampus—a pair of structures whose shapes each resemble
that of a sea horse. If a hippocampus is damaged or removed, we lose the ability to form new long-term memories; old memories remain, but new ones do not form. Thus, the hippocampus plays some crucial role in forming long-term memories. Further, it communicates with the cortex through two bundles of axons, one apparently for input and another for output. This suggests that the hippocampus may act, in effect, as a buffer between short-term and long-term memories.\(^\text{[1]}\)

Perhaps when many networks in the cortex are busy—attacking a hard problem—the cortex is too preoccupied to continue the structural changes that produce long-term memories. Perhaps, instead, networks in the hippocampus are activated, loading the buffer. Later, when networks become available in the cortex (perhaps during rest, or sleep), the hippocampus “replays” important patterns in the cortex,
thereby creating long-term memories in the cortex.\(^\text{[2]}\) If such a scenario is true, then all memories are formed by repetition; the difference between procedural and episodic memories is merely that procedural memories are created by conscious repetition, while episodic memories are created below consciousness via repetitions instigated by the hippocampus.

**Posing Problems by Repetition**

We invest time and effort in learning so as to realize future benefits; this implies that we intend to remember what we learn. Problem posing is the level of understanding at which we use repetition for learning how to solve problems and for creating memories of the solution procedure. We identify two kinds of repetition: rehearsal, in which we repeatedly pose and solve the same problem, and variational, in which we pose and solve new problems that are closely related to the original problem.

**Rehearsal** • Having solved a problem, we rehearse the procedure to learn how we solved it. Since we know that the procedure leads to the solution, our minds during rehearsal are free to consider (1) why each step is important and how it contributes to the solution, (2) whether alternative steps may be more economical, and (3) whether the steps and intermediate results can be connected to other things we know, thereby attaching additional meanings to the procedure, the solution, and the problem.

Thus, part of our activity during rehearsal is to probe and verify the logic of the algorithm; such activity conforms to Poincaré’s statement that in a chain of logic, the order of the elements is more important than the elements themselves.* Another part of rehearsal is the search for a better algorithm. That is, problems are interesting and instructive to the extent that they can be solved in more than one way. Problems can themselves be viewed as patterns with their multiple meanings reflected in the various ways by which they can be solved. By repeatedly posing the same problem to ourselves, we create opportunities for finding alternative solution procedures and therefore for finding additional meanings.

A powerful motivation for rehearsal occurs when we intend to present the solution to others—perhaps as a lecture or as a written document. Such presentations are most effective when the chain of logic is economical, with every element moving the development in an obvious way toward the goal. Such presentations are developed by rehearsing, wherein we systematically try to reformulate a logical development into

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a sequence that is not only economical but also rich in meaning. Minsky has emphasized that reformulation is the central act of creativity. For example, in spite of the common attitude that rehearsal is merely mechanical repetition, the rehearsal involved in preparing lectures and writing textbooks provides opportunities for high levels of creativity and originality.

**Variational** • Besides repeatedly posing the same problem, we should also pose and solve other problems that we create by systematically changing the original problem. Thus, we enhance problem-solving skills by posing variations on a theme. This activity is analogous to a practice technique used by musicians. Consider the passage from Chopin’s third Prelude (Opus 28) for piano, shown in Figure 1. This one measure is scored as a phrase—a musical pattern of sixteen notes. The third Prelude is marked vivace, which means a lively allegro, and corresponds to a speed of about a measure per second. In fact, a measure per second would be a little slow; five measures in four seconds would be more nearly correct. Thus, each of the sixteen notes should be sounded at a uniform interval of about 5/100 of a second.

How is such skill developed? Not simply by repeatedly playing the measure as written, but rather by practicing rhythmic variations, such as are also shown in Figure 1. Each variation shifts the emphasis to a different note, hence a different finger; additional variations would be used to shift the emphasis among different groups of notes. The figure shows only three variations, but in practice, the musician routinely works through 40 or 50 variations of the same phrase. And those are just the rhythmic variations; one also works through variations in tempo and in dynamics (loudness). It may seem paradoxical that to achieve what the composer has written, one practices something other than what is written, but such practice proves to be an efficient way to attain absolute control over the material; to embed a metaphor within a metaphor, a chain is made stronger by systematically and repeatedly strengthening one link at a time.

Likewise, we can improve our grasp of and control over technical material by posing variations on the theme inherent in any problem. Say the original problem requires us to obtain the volume $V$ occupied by one mole of nitrogen at $P = 2$ bar and $T = 50^\circ$C. Having obtained the answer, we can systematically vary that problem to create somewhat different, but related, problems to solve. For example: (1) What would $V$ be if $T$ were 100$^\circ$C instead of 50$^\circ$C? (2) What would $V$ be if $P$ were 3 bar at 50$^\circ$C instead of 2 bar? (3) What would $V$ be if we had 5 moles instead of one at 50$^\circ$C, 2 bar? (4) Can we generalize what we’ve learned from these four calculations? (5) What if we knew $N$, $V$, and $T$ and needed to find $P$? (6) What if we knew $N$, $V$, $P$ and needed $T$? (7) If the gas were a binary mixture of nitrogen and oxygen, what would change in all these calculations? (8) What if the gas were a twenty-component mixture? (9) Presumably, we have used the ideal-gas law in these calculations, so by what criteria do we decide that the ideal-gas law no longer applies? (10) When the ideal-gas law doesn’t apply, what should we use instead?

Note that the original problem has led us to devise ten variations—effectively, ten new problems. This process is most effective if students are merely shown the strategy and they create their own variations. Hopefully, they eventually create problems that they don’t know how to solve, then they initiate a dialog with the instructor. This process is systematic and can be applied to any problem; in fact, rather than solving 100 different problems, students seem to...
gain more by solving ten problems plus ten variations of each. More on variational problem posing can be found in a book by Brown and Walter.\[4\]

Earlier we noted that reformulation is a central aspect of creativity; this observation can now be pushed farther by noting that devising variations on a theme is itself a reformulation. Hence, as Hofstadter has discussed,\[5\] variations on a theme is the crux of creativity. Any new object, process, or idea is created by modifying, to a greater or lesser extent, existing objects, processes, and ideas. (There is, after all, nothing new under the sun.) This aspect of creativity undoubtedly reflects the way minds work—not by spontaneously creating a completely new neural net, but rather by continually modifying existing assemblies of neurons. But the lesson here is that in practicing variational repetition on solved problems students practice creating new things. And even though their first attempts are mundane and uninteresting, the habit, once acquired, can eventually serve them well.

**Transition:**

**Level 5 (Posing Problems) to Level 6 (Making Connections)**

**Motivation:** Having learned to solve a problem, we should then ask whether that knowledge can be applied to other problems within the same domain and to analogous problems in other domains.

**Reformulation:** Pattern, problem context, and solution are generalized to other domains.

**LEVEL 6: MAKING CONNECTIONS**

The understandings gained at Level 5 can require substantial effort and labor because they often require us to make substantial modifications to dendritic trees and neural networks. So once such modifications are made, we try to increase their usefulness by connecting them to other networks that represent other patterns and problem contexts. That is, we try to project our newly acquired understandings into other domains of knowledge. Sometimes ideas for cross-domain connections can be evoked by posing a simple heuristic: Having solved the immediate problem, can we now solve a similar problem or an analogous problem? But more often, we must employ cross-domain devices to help us find ideas that transcend domains. Cross-domain devices are relations, patterns, or procedures that are invariant under changes of context; thus, they can be extracted from one context and inserted into another. Such devices provide powerful ways to increase understandings, and therefore it is probably not surprising that relatively few of them are known. We are always seeking to add new cross-domain devices to our repertoire, for every such device gives us another way to learn. Five common cross-domain devices follow.

1. Our most powerful cross-domain device is mathematics. This statement often surprises students, for they tend to view mathematics as a tool for computation. But the real value of mathematics is that its rules for reasoning are independent of context: mathematics is powerful because it is abstract. As a simple example, consider the exponential growth law

\[
y = y_0 e^{\alpha x}
\]

where \(\alpha\) may be positive or negative. This one equation applies to certain processes in a number of very different and unrelated contexts. For example, it describes the decay of radioactive isotopes, the variation of density with altitude in a stagnant isothermal atmosphere, the growth of a population in a limitless environment, the cooling of a warm body in cooler surroundings, and the growth of capital in an interest-bearing investment.

2. A second device for extending ideas across domains is provided by scaling laws. These devices exploit the extent to which certain behaviors are universal—indeed, independent of context—when variables describing phenomena are scaled appropriately. Thus, we have the many dimensionless groups that correlate fluid flow and heat transfer in transport phenomena, we have corresponding states ideas for correlating thermodynamic properties, and we have scaling laws for describing the behavior of materials near critical points.

More generally, we now have numerous disparate phenomena, referred to collectively as analogies, that are invariant under changes of scale. For example, the Brownian motion, first described by Robert Brown in 1828, originally referred to a microscopic scale; when viewed through a microscope, a minute particle displays random movements caused by collisions with molecules of the surrounding medium. But such movements are also observed on macroscopic scales in colloidal suspensions and on galactic scales in the motion of stars in open clusters, such as the Pleiades.

3. Another effective way to cross domains is by using an analogy: the presumption that if two things have certain similarities, then they also have other similarities. Analogies can be structural or functional, and it is wise to keep clear which you intend in a particular case; the common pitfall is to assume that structural similarities imply functional similarities. Examples of fruitful analogies include those among the linear transport laws of Newton, Fick, Fourier, and Ohm. In thermodynamics, certain phase diagrams for vapor-liquid equilibria are structurally analogous to diagrams for liquid-solid equilibria. And in process control, artificial neural networks bear certain functional analogies to biological neural networks.

4. Still another device is the metaphor, which we use to describe an unfamiliar thing in terms of some more familiar thing. Unlike an analogy, a metaphor typically attempts to
relate two things that have neither structural nor functional similarities. Minsky has emphasized that we typically use spatial forms and concrete objects as metaphors for abstract ideas and concepts. For example, we talk about an idea being solid, firm, fluid, or off-the-wall. More generally, we have family trees, the tree of life, the tree of knowledge, dendritic trees, and logic trees; we have roots of a family, the root of an idea, the root of the matter, the root of a problem, and the root of all evil; we have bridges between domains of knowledge, the bridge of time, a bridge over troubled water, and a bridge (no less) to the 21st century. One of the most compelling metaphors of recent years has been that of the desktop for manipulating operating systems on personal computers.

The last cross-domain devices we mention here are various graphing templates for representing relations. The most common is a simple x-y plot, which shows how an effect is correlated with its cause. To have something less familiar, we show in Figure 2 examples of an interaction square, which shows how two causes either reinforce or compete in contributing to a single effect. In the first and third quadrants of the square, the two causes act together to either amplify (quadrant I) or suppress (quadrant III) the effect. The interesting behavior occurs in the second and fourth quadrants, in which the two causes compete. If we have a mathematical relation for how the two causes contribute to the effect, then we can usually solve for the locus along which the two causes exactly compensate for one another. This locus transverses the second and fourth quadrants. A particular example appears in the bottom of Figure 2, which shows how temperature and flow rate contribute to a particular value of the Reynolds number for fluid flow.

In the discussion of Level 3 (Paper 2 of this series), we observed that organizing knowledge into patterns provides a mechanism for improving the efficiency of education. Understanding at Level 6 provides a similar opportunity for efficiency. At this level our intention is to find existing neural structures created in one context and apply them to problems in other contexts. When this can be done, we avoid much of the laborious effort required at Level 5 in making major structural changes to old networks.

Transition:

**Level 6 (Making Connections)**

to

**Level 7 (Creating Extensions)**

**Motivation:** Having learned to recognize and solve analogous problems in various domains, we should ask what problems can still not be solved, but which might be solved if we could extend, modify, or reformulate what we have learned.

**Reformulation:** Generalizations are modified to attack other problems.

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**LEVEL 7: CREATING EXTENSIONS**

At Level 6, our understanding is sufficient for us to realize that a certain pattern, problem, or procedure, devised in one context, can be useful when transplanted in toto to another context. At Level 7 we realize that a complete transplant will not be useful, but if the pattern, problem, or procedure is modified, then the transplant will bear fruit. In some situations, the necessary modification can be generated by merely devising a variation on a theme, but more likely, we need a reformulation that is more elaborate than a simple variation.
That is, we are seeking a homomorphic projection across domains—a projection that identifies the essential features and that suppresses the inessential details.

An example is Maxwell’s development of his theory for electromagnetic fields, which grew out of an analogy with vortices created in rotating incompressible fluids, as described by Helmholtz and Thomson. Here is Maxwell reviewing some of Thomson’s papers on electrostatics and magnetism:

... illustrations of magnetic force ... are not put forward as explanations of magnetic force ... They belong more properly to that remarkable extension of the science of hydrokinetics ...

(The first italics is Maxwell’s; the second is mine.)

Creating extensions is a first step in the more general topic of pattern posing and as such it links the study of established patterns to the research involved in creating new patterns. A principal strategy for posing new patterns is to shift, remove, or otherwise violate boundaries. By boundaries, we mean the assumptions and preconceptions that are inherent in any established pattern, concept, or procedure. Even experimental work involves assumptions; that is, we design an experimental protocol involving certain pieces of equipment under the preconceptions that certain phenomena will be observed and not others. But bounds serve as barriers that limit our thinking. So when a problem does not yield to attacks using established patterns and procedures, then we should test the bounds—examine our assumptions and preconceptions. As Root-Bernstein has noted,

in such situations it’s not the problem that causes our lack of comprehension; rather, the impasse arises from assumptions that we take for granted.

Bounds are a product of negative thinking. Up to now, this paper has focused on positive thinking—on identifying ways to promote firing of useful patterns of neurons. But the brain has both inhibitory and excitatory synapses, so not only can we learn productive ways to think, but we can also learn to avoid unproductive ways to think. By imposing bounds on positive thinking, negative thinking helps us be more effective because it helps us avoid wasting time on unproductive and counterproductive trains of thought. But we don’t want the bounds produced by negative thinking to be too rigid because creative extensions can sometimes be found by shifting those bounds or by recognizing that some bounds have been misinterpreted or are inappropriate. Achieving a balance between positive and negative learning requires a delicate hand on the part of the instructor, for overemphasis on negative thinking can easily suppress creative impulses in students.

Lastly, note that violating bounds—juxtapositioning the incongruous—is a principal attribute of intellectual humor. Indulgence in intellectual humor exercises the mind in violating bounds and produces combinations of thoughts that might otherwise remain unconnected. It is a conceit of mine that such exercise preserves some flexibility in neural networks, and it might—just might—represent some lowly practice at creating extensions.

**CONCLUSIONS**

In this series of papers, we have presented a strategy for studying technical material; the strategy is organized into a hierarchy of seven levels. We enter the hierarchy at Level 1 when our attention is drawn to a topic and we begin to pose questions about it. We leave the hierarchy, as it applies to a particular topic, at Level 7 when we begin to consider how the topic’s objects and concepts can be modified so that they can be applied to other topics. Note that problem solving, at Level 4, occupies the central level in the hierarchy, but problem solving is neither the goal nor terminal point of the hierarchy.

An overriding theme of these papers has been that anything interesting or useful has multiple meanings, and understandings of those meanings arise out of connections: connections among objects and concepts to form meaningful patterns, connections between patterns and a problem context, connections among different problems and their contexts, and connections among different domains of knowledge. The hierarchy of understanding provides a scheme for systematically making connections. The hierarchy can be used by instructors to help organize how material is presented to students and to help assess student understanding. Similarly, it can be used by students to help organize their study of a topic, to assess their comprehension, and to identify what should be done to move to the next level.

We have devoted considerable effort in trying to find meanings for the word *understanding*. Perhaps some additional insight can be gained by inverting the issue and identifying things that are *not* understanding:

1. **Verbal fluency is not understanding**—people can engage in conversations about a topic without being able to answer questions about the topic or to explain the topic to others;
2. **Experience is not understanding**—people routinely use automobiles and computers without understanding how such things work;
3. **Solving a problem is not understanding**—people can solve a problem without realizing how they solved it and without being able to explain their procedure;
4. **Making predictions is not understanding**—before 500 B.C., the ancient Babylonians had correlated sufficient observations so that they could predict lunar eclipses, but they could not explain the geometry that causes an eclipse;
5. **Accumulated knowledge is not understanding**—the Nobel laureate Albert Szent-Györgyi once remarked...
HELPFUL HINTS FOR EFFECTIVE TEACHING

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A few years ago, when I was new as Chair of Chemical Engineering at the University of Colorado, my colleagues and I felt the need to take action to improve our teaching. The idea was born, in part, out of a sense of frustration in trying to communicate effectively with students in the face of increased enrollments in our courses at the time.

As a starting point, we held a brainstorming workshop attended by (nearly) all faculty. We next formed small groups, each with the same task of making a list of effective teaching attributes. Each group then presented its findings, which were discussed and organized into four categories:

- Course Organization and Preparation
- Classroom Communication
- Rapport with Students
- Assignments, Examination, and Grading

In preparation for our workshop, I prepared a handout of hints for effective teaching that I later revised with the insights gained from the workshop. Since it is easy to lose focus of our primary responsibility as educators and to fail to set aside ample time for helping our students learn, I make it a habit to review these hints several times a year. I have also given this handout to our all of our faculty.

What follows is the most recent version of the handout, with annotations in italics added for this article. The reader should understand that it is not a systematic or complete scholarly work on teaching, but rather one that has evolved from my experiences and those of my colleagues. In this sense, it has a similar flavor to several other recent articles[1-3] on personal perspectives, and many of the conclusions are ones of common sense and experience. I encourage the reader to also consult more thorough studies and discussions of teaching methods and learning styles.[4-6]

### COURSE PREPARATION AND ORGANIZATION

- Ask to teach courses related to your expertise. Your knowledge of the material and your enthusiasm, both ingredients of effective teaching,[2] will be highest in such courses.
- Outline the entire course in advance. A logical presentation of the material will be most effective if you decide up front what the course learning goals are, what topics are to be covered, and how much time should be spent on each topic, and then prepare a detailed (two to four pages) numbered outline that is used throughout the course.
- Prepare well-organized notes for each class period. It is easy to get into (and hard to get out of) the pattern of preparing for a class the night before (or even the same day). While this approach works for some of my colleagues, I am more relaxed if I prepare a week or more in advance.
- Set aside at least thirty minutes right before each class period to review the materials and to focus your thoughts.
- Read and assimilate several sources in addition to the assigned text. Your course should have your personal touch and should be prepared in a style and sequence that makes sense to you, rather than just following a text. I recommend that you go through several books, journals, popular press, and notes from other faculty to

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select your materials.

- On the first day of class, give the students a course syllabus that includes the course goals, an outline, reading assignments, homework expectations, exam schedule, and grading policies.
- On the first day of class, and periodically throughout the term, discuss the relevance of the course material to practical applications and to the rest of the curriculum. If we want students to learn, then we must provide motivation on why the material is important. Even better, ask them to brainstorm on real-life applications and tie-ins with other courses, either in small groups or in an open-class discussion.
- Provide and discuss review sheets prior to each exam. These help the students see the big picture of what they (should) have learned and how it ties together.
- Your course outline, notes, and materials should be reviewed and updated each time you teach the course.

**CLASSROOM COMMUNICATION**

- Put an outline on the board and provide a preview at the beginning of each class period, whether giving a lecture or using another style; use a brief review of the previous class period as a transition.
- Summarize the key points, with the help of students, at the end of each class period.
- Come to class well prepared and undistracted, so that you are less likely to stumble over derivations or solutions. If you do make a mistake, admit your error. If you get stuck, promise the students that you will find the answer for next time; do not bluff.
- Do not read your notes to the students. *Simply reading lecture notes or from a book is a sure way of turning off the students' learning processes.* While some gifted faculty can deliver an entertaining and factual lecture with no written materials, I am most comfortable with a middle-of-the-road approach where I bring about five pages of handwritten notes to a 50-minute class period—about half of them represent material that I put on the board for the students and the rest is highlighted prompts to me on questions, illustrations, stories, etc.
- Write neatly on the board or overheads, use visuals, and give students sufficient time to take notes. Board use should follow an orderly and logical progression, the physical layout of which should be visualized in advance, and include numbered headings consistent with the course and class outlines. Visuals (pictures, drawings, graphs, charts, etc.) are excellent learning tools. When using overheads, it is especially important to give students time to write down what is necessary—or to provide them with copies of the overheads. I like a mix of writing on the board for the main part of the lecture, interspersed with breaks where I pass out a one-page handout of an example or derivation that I then go through quickly using an overhead.
- Ask questions in order to maintain the students’ focus and assess their understanding of the material. Well-formulated questions should stimulate the students’ thought processes. Give the students plenty of time to answer the questions, and provide prompts or hints, if necessary. I sometimes call on students by name; this must be done with courtesy and respect, as some students prefer to remain in the background. A student must never be embarrassed or ridiculed for not knowing the answer.
- Use examples in class that students can relate to. In a heat-transfer course, discuss why the same temperature “feels different” in dry air, humid air, water, and wind. In a fluids course, calculate how much the shower temperature will go up when the toilet is flushed, and suggest an alternative plumbing design that minimizes this effect.
- Start and end the class period on time, and gently but firmly maintain order.

**RAPPORT WITH STUDENTS**

- Learn each student’s name. While this is more difficult with larger classes, suggestions include asking each student to write a short biographical sketch on the first day of class, taking photographs, handing back homework individually just before the start of class, greeting students by name, and asking students their names when you don’t know them.
- Schedule at least two office hours or optional-help sessions per week at times available to the students. One should be the day before an examination is held or homework is due, and the other(s) earlier in the cycle.

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Most important, be present for your office hours and inform the students and reschedule those times for which there are unavoidable conflicts.

- Be willing to see students outside scheduled office hours and help sessions. One of the most difficult issues we face is how to make availability to students a high priority when there are so many other demands on faculty time. When students drop by, my intention (though I often fall short) is to set other things aside and listen and help. If meeting their needs will take longer than I can spend at that time, then I set up an appointment. To make the necessary uninterrupted time for writing and other tasks, I come in early; others may prefer to stay late or spend part of the day working at home.

- Be attentive and sympathetic to students; do not say anything that might make a student feel put down, either in public or in private. The most common student complaints that I receive as Department Chair is that they have not been treated with respect by faculty. While insensitive words or actions are often unintended, we must never lose sight of our calling to serve and encourage our students.

- Take at least one class period, or parts of two or more, to dispense with the course material and discuss a subject such as professional ethics or your own experiences.

- Solicit and respond to mid-course feedback by a group interview or evaluation questionnaire. Using class representatives or peer evaluation can also yield useful feedback while there is still time to make changes.\[3\][1][1]

- Provide food. At help sessions, during special occasions in class, or for an end-of-term party.

- Understand that relationships with students do not end with the course. If you show students that you care, then they will naturally ask you to write recommendations and provide career advice.\[2\] Some will come to you with personal problems (know when to seek help from campus professionals). Some will stay in touch for years. These are some of the responsibilities and rewards of our profession.

**ASSIGNMENTS, EXAMINATIONS, AND GRADING**

- Inform the students of the course grading scale or method at the start of the course. The second most common complaint that I receive from students involves grades—that they were not informed by the instructor that a certain exam would make up half of their grade, that they were not told what performance was required to get a "B" in the course, or that a friend received a higher grade with the same or lower scores.

- Make sure that the exam problems correspond to the course objectives and learning goals, which should be the major topics of the class periods and homework assignments. Students learn more when they are actively involved.\[7\] and one of the best activities is homework on carefully selected problems.

- In each assignment and examination, include a mix of simple, medium, and difficult problems. Since students learn and demonstrate knowledge in different ways, it helps to include a variety of exercises.\[7\]

- Develop solutions for all homework and exam questions before they are handed out, and work the problems yourself. Not only does this serve as a check that the problems are reasonable, but it also gives you the necessary preparation for answering questions.

- Grade as thoroughly as time allows, providing comments and partial credit. Careful grading is needed for fairness and consistency, and it provides important feedback to the students. This requires time; if necessary, use this article to help convince your department to invest adequate resources in graduate and undergraduate course assistants.

- Return graded homework, exams, and reports promptly. Students want feedback.\[7\] More important, prompt grading shows students that they are a high priority.

These hints for effective teaching can be summarized in one word: *time*. It takes time to prepare a course well; it takes time to know students. If we care deeply about students and their learning, then teaching will be a high priority among our other responsibilities and we will take the time to do it well.

**REFERENCES**

Toward Technical Understanding
Continued from page 35.

that during his study of muscular action he came to realize that the more he learned, the less he understood, and so he became fearful of finally learning everything, but understanding nothing.\[10\]

The discussions here raise many questions that would seem to serve as starting points for further, more detailed investigations. Here is a list of some of the more obvious ones.

1. If the pattern can indeed serve as the fundamental unit of understanding, then what are those patterns that distinguish one topic from another? For example, what patterns distinguish transport from thermodynamics and thermodynamics from reaction kinetics? Then, by extension, what patterns distinguish chemical engineering from chemistry and from other engineering disciplines?

2. Repetition is necessary to solidify certain kinds of understandings, and therefore some amount of redundancy needs to be incorporated into a curriculum. But efficiency in education can be attained by appealing to patterns and other devices that cross subject domains. To what extent can a curriculum be made more effective by organizing it around patterns rather than topics?

3. What are appropriate cues that will activate, in student brains, proper patterns and homomorphic projections needed to address particular problem situations? Are there minimum numbers of cues that are sufficient?

4. Can we contrive a complete list of devices for making connections across subject domains? Is there a minimum number of such devices that a student should be able to use? What are the most effective ways for students to develop facility with cross-domain devices?

5. Can we devise systematic procedures for identifying and testing default assumptions and probing tacitly assumed boundaries?

6. Are there ways to gauge the importance and impact of negative thinking relative to positive thinking?

7. What indicators can we devise for determining when students successfully make a transition from one level of understanding to another?

8. Presumably, we do not expect all students to achieve the same levels of understanding. What levels are appropriate for BS students? For MS students? For PhD students?

9. Traditional descriptions of brain function use time to identify two kinds of memories: short-term (you look up a phone number and remember it only long enough to dial it) and long-term (you still remember your name). But recent evidence suggests a third: intermediate-term memory, in which a buffer (perhaps the hippocampus) is loaded while structural changes are made in the brain to lay down the corresponding long-term memory. Thus, students who cram before a test often do not retain the crammed information because they are only loading a buffer, not creating long-term memories. This suggests that simple linear progression through material over a semester may not be as effective as some cyclic procedure in which important patterns are revisited at intervals. Revisiting amounts to repetition, which stimulates creation and solidification of long-term memories and pares away superfluous scaffolding. If this conjecture were confirmed, what kinds of cyclic presentations should be used? What are the optimum times between re-exposure to the same patterns?

10. Finally, note that throughout these papers we have emphasized what rather than how. So, how do we help students progress through a hierarchy of understanding?

Understanding never ends.

Minsky\[3\]

ACKNOWLEDGMENTS

Many of the ideas presented in this series were tested and clarified by continually referring to Marvin Minsky’s book,\[3\] The Society of Mind; without that book, these papers would have taken a very different form. Over the years of my struggle to understand understanding, I have learned much from discussions with my colleagues R.W. Rice (Clemson) and J.P. O’Connell (Virginia); my thanks for their forbearance.

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EXPERIMENTS ILLUSTRATING PHASE PARTITIONING AND TRANSPORT OF ENVIRONMENTAL CONTAMINANTS

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Historically, chemical engineers have been primarily concerned with maximizing the efficiency of individual processes while designing chemical production facilities. Current regulatory pressures to minimize risks associated with the production of chemicals, however, require chemical engineers to understand the fate of these chemicals in the environment. The fundamental mass transfer processes controlling the migration of contaminants in environmental systems are similar to those in chemical engineering processes. There are distinct differences, though, that have implications in how individual processes are analyzed. For example, contaminant concentration in the environment is generally very low (on the order of parts per million (ppm)), and the number of compounds present in a given environmental system is very large and unknown compared with typically well-controlled chemical engineering processes. The complexity of these systems needs to be simplified in order to describe mass transfer process environmental systems.

At Clarkson University, the fate of hazardous organic pollutants in the environment is covered in the class “Hazardous Waste Management Engineering.” Senior-level students from the departments of civil and environmental engineering, chemical engineering, and industrial hygiene typically enroll in this class. Fundamental processes governing the environmental fate and transport of organic contaminants are covered during introductory lectures and are used throughout the semester to support more advanced material related to human exposure levels, risk assessment, and design of treatment strategies. Throughout the semester, the relationships between chemical behavior and molecular structure (i.e., size and polarity) are emphasized.

After this class was taught for two years, it became apparent that students had difficulty grasping the concepts of partitioning of solutes between phases. Thus, the experiments described here were developed to help students understand the partitioning and transport of organic compounds in environmental systems. Constraints of class length (50 minutes), size (30-40 students per section), and budget, however, limited the scope of possible experiments. A creative solution of using nontoxic, colored solutes, allowing strikingly visual detection as the solutes partitioned between phases, effectively illustrated the concepts of phase partitioning and enabled all students to be active participants in both the qualitative and quantitative components of this laboratory.

BACKGROUND AND THEORY

A significant fraction of groundwater contamination in the United States is the result of spills and disposal of organic liquids in the ground. The organic phases, referred to as non-
aqueous phase liquids (NAPLs), are typically considered to be "immiscible" with water, although their solubilities are high enough to contaminate groundwater at levels higher than drinking-water quality standards. Figure 1 illustrates the partitioning and transport processes affecting a NAPL such as gasoline. Since gasoline is less dense than water, it accumulates at the water table. Subsequent partitioning of contaminants into both the groundwater and soil gases will occur.

The equilibrium dissolution of solute from a NAPL and subsequent sorption of the aqueous-phase solute to sand are considered in this laboratory. Because of the low concentrations involved in these processes, it is assumed that the density and molecular weight of the phases, and activity coefficients of each species in the aqueous phase, remain essentially constant. For many NAPLs, it is reasonable to also assume that the organic phase is an ideal solution and, thus, that activity coefficients in this phase are close to one.

Fundamental processes governing the environmental fate and transport of organic contaminants are covered during introductory lectures and are used throughout the semester to support more advanced material related to human exposure levels, risk assessment, and design of treatment strategies.

\[
\text{NAPL-water systems: } C = C'X \quad (1)
\]
\[
\text{Soil-water systems: } q = K_d C \quad (2)
\]

where
- \( C \) concentration (mg/L) of a compound in the aqueous phase
- \( C' \) solubility of the pure liquid chemical in water (mg/L)
- \( X \) mole fraction of this compound in the NAPL
- \( q \) concentration sorbed on the soil (mg/kg)
- \( K_d \) soil-water distribution coefficient (L/kg)

Equation (1) is Raoult’s Law for liquid-liquid equilibria and has been shown to be fairly accurate for even complex NAPL mixtures comprised of chemicals with low solubilities.\(^{[1]}\)

Both \( C' \) and \( K_d \) are partition coefficients describing the linear equilibrium relationship between phase concentrations. Their values are highly dependent on the molecular structure of the compound.\(^{[3]}\)

Nonpolar organics are hydrophobic, exhibiting trends of generally decreasing solubilities and increasing soil-water distribution coefficients with increasing molecular weight. The presence of polar functional groups, especially those with O, N, or S atoms, decreases the aqueous-phase activity coefficient, thereby greatly increasing the aqueous-phase solubility and decreasing the soil-water distribution coefficient of organic compounds.

Following the partitioning of organic compounds from the NAPL to the aqueous phase, the contaminant molecules are transported with flowing groundwater, potentially polluting downgradient sources of drinking water. Convection (also called advection by environmental engineers) and dispersion are the predominant transport mechanisms, although the sorption of solutes to soil effectively retards the transport rate. Assuming equilibrium between solid and the liquid phases, the standard transport equation with a linear sorption term added can be written in one dimension as

\[
\frac{\partial C}{\partial t} = D_1 \frac{\partial^2 C}{\partial x^2} - u_x \frac{\partial C}{\partial x} + \frac{\rho_b K_d}{n} \frac{\partial C}{\partial x} \quad (3a)
\]

or

\[
\frac{\partial C}{\partial t} = D_1 \frac{\partial^2 C}{\partial x^2} - u_x \frac{\partial C}{\partial x} + \frac{\rho_b K_d}{n} \frac{\partial C}{\partial x} \quad (3b)
\]

where
- \( D_1 \) hydrodynamic dispersion coefficient in the longitudinal direction
- \( u_x \) average linear interstitial velocity of the aqueous phase
- \( R \) retardation coefficient \( (R = 1 + \rho_b K_d / n) \)
- \( n \) porosity of the porous medium
- \( \rho_b \) bulk density of the porous medium

The retardation coefficient can also be described as the ratio of the mean velocity of water \( (u_x) \) to the mean velocity of the solute \( (u_{x,sol}) \)

\[
R = \frac{u_x}{u_{x,sol}} \quad (4)
\]
A solute with a low retardation coefficient (R~1) will be relatively mobile within an aquifer system, potentially resulting in higher human exposure levels than a solute that sorbs strongly.

**EXPERIMENTAL DESIGN AND RESULTS**

A laboratory experiment was developed to reinforce the concepts of phase partitioning and its relationship to molecular structure and the mobility of a solute in a groundwater system. Three NAPLs with different colors and hydrophobicities were mixed with water, and then the contaminated water infiltrated through sand to observe the partitioning of the colored solutes. This experiment was included in the hazardous waste management class during the fall semester of 1995.

An assessment of the effectiveness of this laboratory indicated that the students perceived an increase in their comprehension of these concepts. Results of their homework assignments, however, showed that they still struggled with quantitative homework problems. Thus, an additional experiment was designed for the 1996 class that involved a more quantitative measure of retardation coefficients as contaminated water samples were pumped through a soil column and the velocity of the contaminant was measured relative to the velocity of water.

**Materials**

- Adding dye to nontoxic organic phases created three NAPLs with different colors and a range of partitioning behaviors. Table 1 describes the composition of the “red,” “blue,” and “green” NAPLs. The polarity (or hydrophobicity) of these dyes is the property critical to their partitioning behavior and the success of the experiment. The overall polarity of a molecule depends on contributions of polar atoms (O, S, N, Cl) and nonpolar atoms (C, H). Qualitatively, oil-red-o is more hydrophobic than methylene blue because a greater fraction of the oil-red-o molecule is comprised of carbon (see Table 1). Similarly, green food color is more polar than methylene blue since the number of polar atoms in green food color is higher than in methylene blue (Table 1). In order for the observed partitioning of the color to be representative of the overall bulk NAPL partitioning, the polarity of the dye has to mimic the polarity of the NAPL. The polarity of the bulk organic liquids used increased from mineral oil to ethanol. Thus the polarity of the selected colors represent the polarity of the NAPL.

Other materials included tap water as the aqueous phase and clean quartz sand, suitable for a child’s sandbox, for the soil.

---

**TABLE 1**

Composition of Colored NAPLs

<table>
<thead>
<tr>
<th>NAPL</th>
<th>Bulk Organic Phase</th>
<th>Solute</th>
<th>Chemical Formula</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>red</td>
<td>mineral oil</td>
<td>oil-red-o</td>
<td>C₁₄H₂₅N₁O</td>
<td>very hydrophobic</td>
</tr>
<tr>
<td>blue</td>
<td>5% (by vol.) octanol in mineral oil</td>
<td>methylene blue</td>
<td>C₁₆H₁₈N₁SCl</td>
<td>slightly hydrophobic</td>
</tr>
<tr>
<td>green</td>
<td>ethanol</td>
<td>green food color</td>
<td>C₁₆H₂₀O₁₂Na₁S₁₂</td>
<td>hydrophilic</td>
</tr>
</tbody>
</table>

1 Only a small amount of dye required for each to provide vivid color
2 Available through Fisher Scientific (biotechnology reagent)
3 Dissolved in octanol prior to mixing with mineral oil
4 Mixture of FD&C Yellow 5 and FD&C Blue 1; available through McCormick & Co. Inc., Maryland
5 FD&C Yellow 5 (5)
6 FD&C Blue 1 (5)
partitioning behavior of the red, blue, and green solutes as well as the bulk organic phases. Teams of 3-4 students each were provided with bottles containing each of the three NAPLs, three 40-mL screw-cap vials about 75% full of water, two filtering crucibles about 50% full of dry sand, two 50-mL beakers, and several disposable capillary pipettes.

In the first phase of the experiment, students observed the range of possible partitioning behaviors between the NAPLs and aqueous phase. The steps simply involved adding approximately 1 mL of NAPL to each of the three water vials, gently shaking them to equilibrate, and then observing the distribution of color and the bulk organic fluid between phases. Results range from no observable partitioning of the hydrophobic red solute in mineral oil to the complete dissolution of the very polar green solute in ethanol (see Figure 2). The blue solute illustrates the concept of having a partially soluble solute in an essentially insoluble bulk organic phase. In this case, much of the blue color transferred to the aqueous phase, although most of the volume of NAPL remained as a separate immiscible phase. This case is most representative of environmentally significant NAPLs such as gasoline.

The second phase of the first laboratory provided a greater understanding of the partitioning of solutes between aqueous and soil phases. As described above, the mixing of NAPLs and water generated blue and green contaminated water. Each of these aqueous phases was then poured through sand in the filtering crucibles that were held over 50-mL beakers. The very polar green solute was not retarded, as evidenced by the lack of change in color of either the sand or water. With the less polar blue solute, however, the sand turned blue and the effluent became clear, illustrating that slightly soluble solutes can be strongly sorbed, greatly decreasing contaminant concentrations in the aqueous phase.

In order to help students increase their understanding of partitioning behavior, we posed several questions to promote their ability to connect experimental observations to fundamental concepts (see Table 2). These questions focused primarily on the relationship between chemical structure and mobility of chemicals in the environment.

| TABLE 2 |
| Questions Posed to Increase Conceptual Understanding |

### Questions for NAPL-water partitioning
- Classify the solubility (soluble, partially soluble, insoluble) of three colored solutes and the bulk organic phases
- Discuss the implications of these differences on the fate of NAPLs in the subsurface
- What differences in the chemical structures would you expect based on the observed solubilities?

### Questions for aqueous phase-soil partitioning
- Rank the solutes in order of increasing potential for sorption; explain your answer
- Discuss the implications of these differences on the mobility of these solutes in the environment
- What differences in the chemical structures would you expect based on the observed sorption behavior?

### Summary questions
- Are the observations and conclusions drawn from the solubility experiment consistent with the results of the sorption experiment? Explain.
- Describe the overall fate of each of the three NAPLs following a spill to the environment

---

**Figure 3.** Schematic of experimental system for column retardation experiment.

**Laboratory 2**

A Quantitative Measure of Solute Retardation

The second laboratory was developed to quantify the extent of solute sorption. The equipment required for this laboratory (see Figure 3) was more extensive and, thus, the laboratory was conducted as a demonstration, with students taking turns making the measurements over time. Colored aqueous phases for this experiment were prepared by the direct addition of dyes into the aqueous phase (0.05 g/L methylene blue for the “blue” aqueous phase and 10 mL/L green food color for the “green” aqueous phase).

Two Plexiglas columns (3.8-cm diameter by 25-cm long) were carefully packed with a uniform sand (30-40 mesh; \(d_{50} = 0.5 \text{ mm}\)) to provide a relatively homogeneous sand to help minimize solute dispersion within the column. Several pore volumes of degassed water were then pumped through each column to displace and dissolve all of the air. At \(t=0\), pumping of the blue and green aqueous phases through the col-
columns at rates typical of groundwater flow \( Q = 0.1 \text{ mL/min} \) was initiated.

Using colored solutes allowed visual assessment of the migration of these solutes. The interface between clean and colored water was marked on each column over time and the average distance traveled by the colored water was recorded. Assuming that convection is the predominant transport mechanism, the position of the sharp front marked by the colored water was used to estimate the interstitial solute velocity. Thus, the retardation coefficient (Eq. 4) was calculated as

\[
R = \frac{Q / A_n}{L / t}
\]

where
- \( Q \) = volumetric flow rate of water
- \( A \) = column cross-sectional area
- \( L \) = distance traveled by the colored water in time \( t \)
- \( n \) = porosity, included to convert to an interstitial aqueous phase velocity

Equation (5) can be rearranged to calculate the retardation coefficient by linear regression of the \( L \)-versus-\( t \) data.

Figure 4 illustrates differences in the travel time of the solutes through the soil columns. As expected from the qualitative experiment described above, the greater distance traveled by the very-polar green solute indicates that it is much more mobile than the less-polar blue solute. The observed variability in the position of the front around the column perimeter at any point in time (Figure 4) is attributed to column-scale heterogeneities in soil permeability that affect local rates of convection. To accommodate for this variability, the experimental analysis was completed using the average of four measured travel distances at each time. These average travel distances with error bars representing ± one standard deviation are included in Figure 5.

Linear regression of the data was used to estimate the retardation coefficients for each solute. Regression coefficients greater than 0.99 were obtained in both cases. The low retardation of the green solute \( (R = 1.4 \pm 0.1) \) confirms the fact that this solute would be highly mobile in an aquifer system, while the higher retardation coefficient for the blue solute \( (R = 4.4 \pm 0.2) \) provides quantitative evidence of the greater extent of sorption of this solute. With both visual and quantitative interpretation of this experiment, students grasped the impact of sorption and the connection between this partitioning process and the potential for exposure to contaminants through drinking water downgradient of a pollution source.

**DISCUSSION AND CONCLUSIONS**

Students completing these experiments observed the wide variability in the behavior of organic pollutants in the environment. They concluded that the mobile green solute and the bulk organic liquid that comprised this NAPL were hy-
drophilic and very mobile in the environment. The solute and bulk organic liquid that comprised the red NAPL, on the other hand, were very hydrophobic and relatively immobile in an aquifer system.

From a pedagogical standpoint, providing students with an active learning experience and very visual observation of these phenomena effectively improved their overall understanding of the fate and transport of organic contaminants in an environmental system. In terms of Bloom's hierarchy of learning,[4] the first laboratory increased the students' comprehension, while the second laboratory addressed the application of these ideas in engineering calculations. Both comprehension and application are critical steps for the students to achieve prior to advancing to the more challenging tasks of analysis and synthesis. Thus, by completing these laboratories early in the semester, students were better prepared for tackling more complex issues associated with formulating engineering decisions with respect to the potential for environmental contamination.

ACKNOWLEDGMENTS

Support from a National Science Foundation CAREER grant (BES-9501567) was used in developing these laboratories.

REFERENCES


COMET Project

Continued from page 23.

for introducing these topics.

As the instructor, I should have made more clear to the students the connections between the project and the course material. I also should have explained why the project is of value to a beginning engineer. Clearly stated instructional objectives are known to facilitate student learning.[5] The project might have been more closely linked to the main course content if, for example, it had permitted chemical energy sources and involved more energy balance calculations in the COMET design. But this would have been difficult since the project had to be safe and relatively short and simple for sophomore students. The COMET project is therefore a compromise that achieves the primary goal of introducing ideas not found in traditional pencil-and-paper projects, but does so in a non-chemical engineering-specific format.

Logistical Improvements

"I think this project would have been better at the beginning of the quarter."

"Give the groups an extra week or so to think about the project."

"Make the project worth more than 5%.

A number of students would have preferred different logistical arrangements for the project. Because it involved a lot of work, students wanted the project assigned earlier in the quarter when it would not conflict with midterms, wanted more time to work on the project, and wanted it to be worth a larger fraction of their grade. All of these changes can be easily made and will be implemented next time.

CONCLUSIONS

The COMET project provided a relatively simple assignment that introduced sophomore chemical engineers to a number of important engineering concepts that are often not addressed until later in the curriculum: teamwork, open-ended problems, design, hands-on experimentation, technical writing, and estimation based on limited data. Most students enjoyed the project and recommended its use in future classes.

ACKNOWLEDGMENTS

Thanks to Melissa Bradley, Richard Felder, and David McGill for helpful discussions and to Dayton Funk for photography. This work was supported in part by a CAREER Young Investigator Award from the National Science Foundation (BES-9624832).

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Winter 1998
Random Thoughts . . .

SHIPS PASSING IN THE NIGHT

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Ever get a sneaking suspicion that our students may not be totally focused on the intellectual delights of thermodynamics and transport phenomena while we’re lecturing? It sometimes happens that other things are on their minds, especially when we’re enthusiastically filling the board with letters, numbers, and squiggles that have no apparent connection to anything they know or care about. For example,

♦ ♦ ♦ ♦

Professor Cheever:
“. . . and next we’ll examine laminar flow of a newtonian fluid in a circular pipe and derive Equation 4.5-35 in your text. We first draw this differential element . . . and now we itemize the stresses acting on it, starting with . . .”

♦ ♦ ♦ ♦

Student A (SA): “Hey Jerry, how’s the rest of your schedule look?”
SB: “Not bad—I’ve got a couple of humanities courses so I shouldn’t be overworked.”
SA: “Unless you got old Ferguson . . . last spring she gave us five books to read in the first week, including Moby Dick. It’s about a fish.”
SC: “What did he say that arrow pointing up is?”
SD: “Who knows? . . . I just wonder how I’m going to make it to December if I’m this lost now.”
SC: “You and everybody else . . . except maybe old Arthur here . . . Hey Art—you getting this?”
SE: “No, but I’ve seen his old tests—you don’t need to understand anything, you just need to plug into formulas.”
SD: “Cool!”
♦ ♦ ♦ ♦

Professor Cheever:
“. . . and as we know from calculus, the limit of this expression as delta r approaches zero is what? . . . anyone remember? . . . no? . . . well, it’s the partial derivative, and so we can replace . . .”

♦ ♦ ♦ ♦

SF: “What say, Chief—coming to the Delta Chi mixer tonight?”
SG: “No can do—I got a physics test tomorrow and if I don’t get my grades up I can kiss my scholarship goodbye.”
SF: “Aw, come on, Sir Isaac—you know that stuff. A couple of brews and you’ll be relaxed and ready to hit that test like a sledgehammer.”
SG: “That’s what you said before the chemistry final last spring and if I remember right you relaxed your butt into a D.”
SF: “Yeah, but that final was . . .”
SH: “So how’d it go last night?”
SI: “Don’t ask . . . that geek Rachel set me up with is majoring in soil science or something and he spent the whole night talking about fertilizer. Let me tell you a
few things about phosphorus that you probably never . . ."

Professor Cheever:

"Now at this point we introduce the stress tensor, a convenient and concise representation of the normal and shear stresses in the . . ."

SJ: "Yo, Sally—hand me some of them chips there."
SK: "... Problem 3 on the thermo homework?"
SL: "Yeah, it's a killer, but it's cute—you have to figure out the equilibrium partial pressure of nitrous oxide to know if the dental hygienist poisoned the bank president."
SK: "Right, I figured that much out, but at that pressure you can't just plug into Raoult's law and I don't how how you . . ."
SJ: "Yo, Gene, can I have a hit of your Dr. Pepper?"
SM: "What time you got—I think this has been going on for about four hours but I'm not sure."
SA: "Twenty minutes to go and counting."

SA: "Ten minutes."
SN: "Shh—don't wake Brenda . . . she's the only one getting anything useful out of this class."
SO: "It's my grandmother this time—I'll probably have to go home for the weekend again and just hope I can find some time to look over the . . ."
SJ: "Yo, Bruce, hand me a couple of them Cheez Doodles, would ya?"
SQ: "Hear about Monica, Sheila's roommate?"
SR: "No, what about her?"
SQ: "She's been acting weird lately, just lying in her room staring at the ceiling for hours."
SR: "Sounds bad."
SQ: "Gets worse—someone found her passed out next to an empty pill bottle yesterday. Sheila saw her at the hospital today and thinks she'll be all right but she still looks kind of green."
SR: "Bummer! That's like what happened to Rudy last year, only instead of popping pills he . . ."

SA: "One minute."
ST: "... ok, now here in Problem 4 what I think we need to do is . . ."
SU: "... so the horse says to the chicken . . ."
SJ: "Yo, Angie, lemme have a couple of those M&M's—I like the orange ones."
SV: "... and at least we got to do something in those class exercises Furze was always giving in mechanics—you make me sit for an hour without doing anything and I'm . . ."
SG: "... no, we're going down to the beach Friday right after class—tell Jack and Ella we'll meet Monday afternoon in the lounge and finish that report, and then we can . . ."
SE: "... but that correlation only works at low concentrations. Maybe if we . . ."

SW (laughing): "That's a good one . . . did you hear the one about the rabbit, the priest, and the chemical engineering professor who were on a . . ."
SX: "... and he's really mad and told Mom that he's not going to pay my tuition any more so I may have to find a job, and I don't think I can stay in school and work enough hours to . . ."
SY: "Hey, Cindy—how about asking him if we're responsible for this stuff on the exam. I love the faces they make when you ask them that."

SA: "... and there's the buzzer, and I'm out of here."
SZ: "Yo, Vinnie, bring your book to the Keg tonight—I got a few questions about Eq. 4.5–237."
SJ: "Hey, no problem—that one's my favorite. Come on—let's grab a burger and fries across the street before we go to the . . ."

SA: "And the point of all that is?"
SZ: "Beats me." □

All of the Random Thoughts columns are now available on the World Wide Web at http://www2.ncsu.edu/effective_teaching/ and at http://che.ufi.edu/~cee/
MAKE SUMMER INTERNSHIP A LEARNING EXPERIENCE

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Many engineering undergraduates have the opportunity to work on one or more summer internships before they graduate. In principle, the students are paid to spend the summer learning how engineering projects are carried out in the real world.

Time out for a reality check. Without significant planning by faculty, the chances of an undergraduate summer intern actually learning something useful are not very good. Unlike graduate students, who usually receive projects consistent with their research expertise, undergraduates are often simply parceled out to various plants or R&D facilities. Rarely are faculty members involved in site or project choices; no one really knows what the students will end up doing, and there is rarely any follow-up to find out if they learned anything of substance.

Let’s review how this process often works. Sometime around March or April, someone on the faculty starts phon-
Project #1, Description
Optimum functionality of our proprietary XLR34 Recombinant Distillation Process requires a complete understanding of the quaternary splits of all components throughout the column internals. The summer intern will be used, as suggested by our Total Quality Management Life Cycle Engineering guidelines, as a resource to speed up the analysis of tray-to-tray hydrodynamics in the XLR34 downcomers. The data will be used to build a simulation (see The Project #2) of downcomer flow stability needed for optimum economic ROI.

Translation
I'm going to have the kid stand in front of that old GC for three months injecting samples and recording peak areas. Aside from stabbing himself with the needle, there is virtually no way the student can get hurt and I'll never have to deal with the safety people or do any of their paperwork. Plus, he'll have an enormous pile of numbers to plot and try to make sense of which will keep him out of my hair for three months and give him at least six overheads to present in the project review in August.

Project #2 Description
The Economic Viability Indices for our proprietary XLR34 Recombinant Distillation Process are very dependent on downcomer hydrodynamic functionality. In order to maximize the R&D Investment Index, as suggested by our Total Quality Management Life Cycle Engineering guidelines, it is critical that fluid dynamic computations be carried out to model the flow striations previously described in our Project Monthly dated 2/9. A suitable computer system has been procured for use by the summer intern. Our goal will be to develop a proprietary computer simulation to describe these striations. In future communications, this program will be code-named Program XLRC to minimize the potential that in-kind competitors recognize our activities.

Translation
We found an old 286 that nobody was using and set it up in the corner of the high bay. Since any program has to be written in QuickBasic to run on this thing, it should take at least three months to get anything working. Aside from eye strain, there is virtually no way the student can get hurt and I'll never have to deal with the safety people or do any of their paperwork. Plus, there will be an enormous pile of code to write and try to debug, which will keep this person out of my hair for three months and give him or her at least 6 overheads to present in The Project Review in August. Best of all, by September 10, nobody on earth will remember what XLRC means, and I can bury the whole business and get on with my life.

The Research Director, having received the project descriptions in a timely manner, passes them on to the faculty advisor. The advisor is quite pleased. These students will really learn something this summer! (Not!)

We have just described two very successful summer internships. I have personally witnessed dozens of them. From the standpoint of the Research Director and the company, the students came in, worked on something presumably useful to the company, and left without having been physically altered. Too bad no one thinks to ask the intern whether he or she actually learned anything useful.

To be fair, we should point out that many companies make an admirable effort to identify appropriate intern projects. In these companies, project ideas are solicited and reviewed by staff engineers (possibly a special committee) prior to intern assignments. Rarely, however, do professors take part in these reviews. While many companies conduct on-campus interviews for summer interns, the results may be undesirable since the professors, again, are left out of the planning process.

Unfortunately, few practicing engineers are able to assess whether a given project is appropriate for an undergraduate chemical engineering student. To test this, just ask a few industrial colleagues to submit problems for the sophomore mass and energy balance course. Don't be surprised if many of the problems are far too difficult for students at this level. We
easily forget how hard those problems once seemed.

**A BETTER WAY**

Setting up meaningful summer internships for your students is possible. But, it takes commitment by the entire department and continuing effort. If you really want your students to learn something useful, try following the route outlined below.

**Establish Contacts with Engineers, NOT with Managers**

It must be very tempting, given everything else you have to do, to simply place that once-a-year call to the R&D Director. Unfortunately, many R&D Directors I have known don’t have a clue on how to define a good internship problem. But if you make the effort to befriend the engineers who actually do the technical work, you can make dramatic progress toward the goal of finding truly excellent summer intern problems. The hard part is finding the right engineers. In addition to using whatever contacts you already have (alumni are excellent contacts), try scanning the programs from recent AIChE meetings for industrial participants who either wrote or co-wrote papers. Chances are good that a phone call and short pitch to these contacts will unearth a number of people interested in working with someone from the university.

Generally, engineers will not have the authority to grant internship funding. If their company is not in the habit of hiring summer interns, you may need to help the engineer outline for management the economics of sponsoring one or two interns. To do this, e-mail or fax the engineer a single page showing the approximate cost for having a student on-site for three months. It should include student salary, travel reimbursement, and housing if appropriate.

**Sell the Program**

Once you have a commitment from the engineer, get the name and telephone number of the appropriate manager and place a call to that person. Be prepared to wait one to three months (or more) for management approval; virtually nothing is done in industry without having one or two meetings. Expect the manager to say something like, “Let me get together with Bob and some of the other engineers to discuss this first, and I’ll get back to you later.” Always get a firm date and time when the manager will “get back to you.” If they don’t contact you within a reasonable amount of time, and often they won’t, get back to them. A certain amount of nagging can be productive.

Managers like to perceive benefits, tangible and intangible, for any and all money they spend. And, you are asking them to spend money on something they haven’t been convinced they need or want. To this end, have a list of potential benefits handy. Mention such things as

- Increased productivity without a fixed cost on the balance sheet.
- Students are well trained and might bring in new ideas and techniques.
- Students often accept positions after graduation with their internship sponsors. This can help hold down recruiting costs.
- Publications that result from internships reflect well on the sponsoring company and its management.
- The sponsoring engineer will have better access to the university and any technical or recruiting help the faculty might provide in the future.

If it sounds like I’m telling you to “sell” internships, I’ve made my point. That is precisely what you are doing and exactly how you should approach the activity. It need not be a hard sell; the best sponsors, long-term, will be those who buy enthusiastically after a soft pitch. All you want is a commitment and a letter from that manager supporting the internships. Once you have this commitment in writing, whether obtained through the engineer or by directly approaching management, you are in a position to start defining the problems.

**Defining the Internship Problems**

You will always know far more than your engineer-sponsor about the capabilities of the students and the types of problems that would be suitable for them. But, the engineer-sponsor knows far more about his or her process than you know and, therefore, presumably knows what the problems are. So, in this phase, you should have two goals:

1) **Learn about the process so you can help define appropriate problems.**

2) **Teach the engineer-sponsor what he or she needs to know to suggest appropriate problems.**

The first goal above should be a short-term activity. If possible, visit the plant or R&D center to learn about the process yourself; do not assume that the engineer-sponsor fully understands the process. Chances are there are many aspects of the process that are not considered “problems” simply because they aren’t presently troublesome. I have never encountered a process that couldn’t be improved in dozens of ways if someone simply paid some attention to the aspects that weren’t “problems.” Many such improvements could result from a three-month internship study. Since the cost of the internship is relatively low and the return on such improvements is usually rapid and measurable, it is easy for the company to justify the work. But, someone has to clearly point out potential improvements or they will continue to go unnoticed.
The second goal (training engineers to define good internship projects) is a long-term investment in your program. After expending considerable time and energy to develop sponsors, you would like to retain them for many years and, as quickly as possible, reach a point where the engineer-sponsors can suggest suitable problems without your assistance.

Good internship problems have certain distinguishing attributes:

- The problem can be approached by a junior or senior chemical engineering student and solved (or good progress can be made) using skills that students at that level can be expected to have or to easily acquire. The analysis or design of a single unit operation is usually appropriate. As an example, suppose a plant has a rotary dryer that uses preheated air for drying, but there is no recycle of the exhaust. How much money could be saved by recycling some of the hot exhaust air? Would the product quality be the same if the dryer is operated at a higher humidity? Would productivity suffer? How much capital investment would be required? Should this change be made? Even though the dryer performance is currently “acceptable,” the operation might be wasting a substantial amount of energy. An analysis of this dryer would make a great three-month intern problem. The solution requires mass and energy balances, understanding relative humidity and psychrometric charts, basic equipment cost estimation, and basic economic-return calculations. Some experimentation might also be needed, but chances are, old company reports will have drying curves for the product at different conditions of temperature and humidity. The student will then also get some practice in doing an internal literature search.

- The problem can be completed (or really good progress can be made) during the time allotted to the internship. Don’t minimize the importance of this attribute. Students quickly become demoralized if they begin a project and then discover they cannot possibly complete it. They find it embarrassing and often discouraging to have to give the customary end-of-internship talk to the technical staff on a half-completed project. For example, an analysis of the entire heat exchanger network in a large plant cannot be carried out by anyone in three months, but an intern could analyze the performance of one small network of heat exchangers (three or four) in that time.

- The sponsor should have already obtained any needed data that cannot be collected in the first month of the study. For example, the analysis of a batch polymerization reactor might sound like a good project, but chances are that the sponsor does not have the necessary kinetic data for the analysis. (If the data existed, someone would have already done the reactor analysis.) If you assign this problem without reviewing the available data, you may doom the student to a miserable summer. The intern may spend the entire summer waiting for analytical equipment to be delivered or, worse, spend the summer trying to get an ancient GC working that never will.

- The project should test and stretch the student’s engineering skills. Does the project require mass and energy balances to be written and solved? Is statistical analysis of data required? Does the project require the student to learn some new chemistry? Are periodic written progress reports required? Is a literature search needed? Beware of project ideas that begin with “We could sure use some help getting the data we need on Project GruntWork…”—it is a sure bet that your student will spend three months standing in front of some infernal apparatus testing one sample after another. The intern learns NOTHING from this type of activity. If a company just wants some data taken, it should hire a temp. You can do better for your students.

- The intern should be safe while working on the project. Most engineer-sponsors will go to heroic lengths to guarantee the safety of their interns. Nevertheless, you should, if at all possible, look over the sponsor’s shoulder on this issue. Ideally, your program teaches industrial safety as an integral part of the chemical engineering curriculum and your students are capable of auditing their own work environments. Give your students practice before turning them out by assigning safety audits as part of your unit operations and design courses.

Complete the Cycle

Defining appropriate projects will be far more time-consuming than arranging internships. Clearly, one or two faculty members cannot do all the work. One good way to spread the work load is to get the students involved. Once given a set of guidelines like the ones above, there is no reason that small teams of students (three or four to a team) can’t work with engineer-sponsors to draft lists of potential projects. If possible, involve yourself in the review process. By observing the ability of your students to assess the project ideas, you will quickly find out whether they have learned the material you’ve been teaching.

In this way, you can help each class identify new projects and problems for the classes to follow. In addition to learning to identify those “hidden” process improvements described above, your students will be learning teamwork, proposal preparation, communication skills, salesmanship, and, hopefully, a bit about obligations to future generations.

ACKNOWLEDGMENTS

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AN INTRODUCTORY ChE COURSE FOR FIRST-YEAR STUDENTS

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Freshman students who have an interest in chemical engineering have several important needs that we feel should be addressed. First, many of them are still undecided about their major and need help making that decision. Second, these students need to receive instruction that provides a broad, integrated perspective to serve as a foundation for subsequent classes. Finally, first-year students need to experience support and encouragement from faculty and other students.

In spite of these needs, chemical engineering departments traditionally have done relatively little for these students, often relegating them to a generic computing class or to a generic freshman engineering class. For example, for many years at BYU, the only “chemical engineering” courses taken by first-year students were a course in FORTRAN programming and a 0.5 credit freshman seminar. But we have recently changed our curriculum to better meet the needs of these students; among those changes has been the development of a new introductory course—the subject of this paper.

GOALS FOR THE COURSE

We began development of a course for first-year students with several distinct goals in mind (summarized in Table 1), with the most important of those goals being

1. To provide knowledge about the chemical engineering field to help students select their major.
2. To provide an integrative foundation for future courses.

We wanted to provide sufficient information about the discipline to enable students to make an educated decision regarding their choice of a major. To meet this goal, we felt it was important for the students to experience chemical engineering reasoning, calculations, decisions, and applications. These experiences should include an introduction to some of the fundamental principles and equations (e.g., Fick’s Law, Fourier’s Law, etc.). To increase learning and interest, we also wanted to help students understand the impact of chemical processing on their own lives and to understand the connection between chemical engineering and their “everyday” experiences. We felt that it was important for the students to evaluate and draw conclusions from numerical results as would be typically done by a chemical engineer. Further, we wanted to expose students to “design” problems that were open-ended and had multiple solutions.

Finally, we wanted the material to challenge the students in order to stimulate their interest and to provide them with a sense of the curriculum’s rigor. This last goal was motivated in part by our prior experiences with survey courses that failed because they did not offer much intellectually to the students entering our department; students felt that such courses were neither challenging nor informative and were essentially a waste of their time.

We wanted this course to play a significant role as part of our undergraduate curriculum by providing a foundation and perspective for subsequent classes. It has been our observation that sophomores, juniors, and even seniors sometimes view each course in their program as an isolated entity, unrelated to the other subjects they have studied. Instead of building on past learning, they often seem to start over with each new subject. Hence, they frequently fail to see the discipline as a whole until very late in their program (if at all). Therefore, a key objective of our course was to provide...
an integrated overview, offering a broad perspective and serving as a framework upon which subsequent courses could be built. That objective included helping the student understand where subsequent chemical engineering courses fit within the larger perspective as well as how knowledge obtained from other disciplines (e.g., chemistry, math, physics, economics, etc.) is essential. In a figurative sense, the introductory course would create a “skeleton” by broad shallow coverage of the discipline, and later courses would add the “meat” to that skeleton.

Additional goals were related to the social needs of the students. It is our opinion that first-year students should have close interaction with the faculty. While some interaction is facilitated by faculty-student socials, required meetings with advisors, etc., our course provides many more faculty-student contact hours than any other method. Of equal importance to faculty-student interactions are interactions between the students themselves. One of our goals for the introductory course was to help develop a “community of chemical engineers” through the use of learning teams and group activities.

CONCERNS

There were several concerns that influenced development of the course and led us to minimize the credit hours and faculty resources associated with it. It was clear that a new course could not simply be added to a curriculum that was already overflowing, especially at a time when we were being encouraged to decrease the number of credit hours in order to help students graduate more quickly. Thus, inserting this course meant reducing the credit hours of more advanced courses, and some faculty questioned the value of such a trade. Also, since a large number of beginning students do not continue in the discipline after their first year, there was concern that an introductory course would dedicate resources to teaching students who would not graduate in chemical engineering. Further, the course we envisioned would need to be developed from scratch since a suitable textbook was not available, thus adding to the required resources.

After some discussion, the department decided to support the course because of the potential advantages that it would offer our students, provided that the course was designed to minimize the resource requirements associated with it. Consequently, the course was designed as a two-credit-hour one-semester course without a laboratory (even though we recognized the value of a laboratory experience for our beginning students). Two credits were made available for the course as part of a general restructuring of the curriculum, and the necessary resources were allotted for development of the course.

THE COURSE

The goals listed in Table 1 had a significant impact on the course’s structure during its development. In particular, our desire to provide an integrated overview required that the individual course topics be connected together in a logical fashion. This integration was accomplished by structuring the course around an engineering design problem that could be solved by designing a simple chemical process. The entire semester and all the material presented in the course were dedicated to the design of that process.

The problem-oriented scenario begins the first day of class when the students are asked to imagine that they “are chemical engineers working for the ABC Chemical Company.” The student engineer receives a memo from his/her supervisor reporting that the contractor who has been disposing of the hydrochloric acid by-product from “our” manufacturing process is going out of business. The memo goes on to ask the student to take responsibility for solving this problem, and the remainder of the course is directed toward leading the student to that solution. This design problem provides the framework for integration of material presented throughout the semester.

The general topics presented in the course are shown in Figure 1, with the approximate amount of time dedicated to each topic indicated by the length of the segment to which the topic title is attached. This two-credit course is designed to be taught in fourteen weeks, the length of a semester at BYU. Written material developed for each of the topics has recently been combined into a textbook, with each topic forming a sepa-
rate chapter. The table of contents of the textbook, shown in Table 2, reflects the detail and sequence of topics treated in the course.

The topics are introduced on a “just-in-time” basis as the solution to the design problem is developed throughout the semester. For example, after discussing strategies for generating and evaluating possible solutions, the decision is made to design a chemical process in which sodium hydroxide is used to neutralize the HCl. Material balances are then taught in order to determine how much NaOH is needed. Spreadsheets are also introduced as an engineering tool. The students are then taught simple fluid mechanics to provide the basis for delivery of the NaOH and HCl from the storage facilities to the point of reaction. This approach continues as issues are considered regarding mixing the acid and base (mass transfer is taught), and cooling the final product to an acceptable temperature for disposal (energy balances and heat transfer are studied). The final step is an evaluation of the profitability of the proposed process (economics are introduced).

By the end of the semester, students have developed skills in several of the subdisciplines that make up chemical engineering and have applied them toward the solution of an engineering design problem. These skills represent a useful subset of those that they will learn in subsequent chemical engineering courses. In order to illustrate the level at which the material is presented, Tables 3 and 4 provide examples of problems used in the course along with the appropriate solutions as presented in the textbook.

Process flow diagrams are used throughout the course to help the students visualize how the different aspects of the course and design problem are connected. Students are introduced to these diagrams and required to use them very early in the semester (Chapter 2). Then, as each new topic is introduced and used to design an additional component of the “process,” the process flow diagram and stream table are updated to reflect the new addition and its relationship to the previous components of the process.

In contrast to the acid-neutralization design problem, the solution for which is developed for the students throughout the semester, the course also features a second design problem, or case study, to be solved independently by student teams. The case study, described in the last chapter of the book, involves the isomerization of meta-xylene to ortho-xylene and requires the use of material and energy balances, the sizing of a pump, reactor, and some heat exchangers, the preparation of a process flow diagram, and the completion of an elementary economic analysis. It is introduced near the end of the semester and provides the students with an opportunity to work together, to learn from each other, and to apply nearly all of the concepts and principles they have learned throughout the semester. Although new material is presented in class during the time that students are working on the case-study assignment, the last few topics (particularly engineering materials and process control) are treated qualitatively and briefly, with minimal homework assignments, to give the students time to focus on the case study. Students are periodically required to inform their “supervisor” in writing concerning the progress made to date on the case study, and a final design report is also required from each team. The xylene-isomerization case study is the only

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**TABLE 2**

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<th>Chapter</th>
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<td>3. Solving Engineering Problems (What Shall We Do?)</td>
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<td>4. Describing Physical Quantities</td>
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<td>5. Steady-State Material Balances (How Much Base Do We Need?)</td>
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<td>6. Spreadsheets (Calculating the Cost of the Base)</td>
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<td>7. Fluid Flow (Bringing the Base to the Acid)</td>
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<td>9. Reaction Engineering (How Fast Will the Reaction Go?)</td>
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<td>10. Heat Transfer (Cooling Down the Product)</td>
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case study currently included in the textbook. Thus, it has been reused from year to year, in spite of the risk that students may copy reports from previous semesters. We have not found this to be a problem so far, probably because of the honor code at BYU, but we do recognize the value of developing additional case studies for future use.

In order to teach first-year students with varying backgrounds, the course was designed with few prerequisites.

### TABLE 3
Example Used in Course

Species A in liquid solution (concentration=0.74 M) enters a CSTR at 18.3 L/s, where it is consumed by the irreversible reaction

\[ A \to C \]

where \( r_{\text{reaction},A} = k_c c_A \) (where \( k_c \) = 0.015/s and \( c_A \) is in units of gmol/L)

What reactor volume is needed so that the concentration of species A leaving the reactor equals 0.09 M? The density can be assumed to be constant.

**SOLUTION** (Note that the steps correspond to the instructions in Tables 5.1 and 5.2.)

Drawing a diagram for this problem:

<table>
<thead>
<tr>
<th>A \to C</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_{\text{reaction},A} = \frac{(0.015/s) c_A}{V} )</td>
</tr>
<tr>
<td>( V_{\text{in}} = 18.3 L/s )</td>
</tr>
<tr>
<td>( c_{A,\text{in}} = 0.74 M )</td>
</tr>
<tr>
<td>( V_{\text{out}} = ? )</td>
</tr>
<tr>
<td>( c_{A,\text{out}} = 0.09 M )</td>
</tr>
</tbody>
</table>

As outlined in Table 5.2, we want to construct a mole balance on A. For this case (for a single input and single output stream), the mole balance becomes

\[ n_{A,\text{in}} + f_{\text{formation},A} = n_{A,\text{out}} + f_{\text{consumption},A} \]

Species A is being consumed, but no species A is being formed, so \( f_{\text{formation},A} = 0.09 \). This, along with substituting more convenient forms for the molar flow rates, gives

\[ c_{A,\text{in}} + \frac{V_{\text{in}}}{V} = c_{A,\text{out}} V_{\text{out}} + f_{\text{consumption},A} \]

The value of the outgoing volumetric flow rate is not specifically given, so we need a total mass balance, which for a single input and single output stream, is

\[ n_{\text{in}} = n_{\text{out}} \]

which, in more convenient terms, is

\[ \rho_{\text{in}} V_{\text{in}} = \rho_{\text{out}} V_{\text{out}} \]

Since the density is constant, this reduces to

\[ V_{\text{in}} = V_{\text{out}} = V \]

We can now calculate \( f_{\text{consumption},A} \) using Eqs. (a) and (b). Equation (a) becomes

\[ f_{\text{consumption},A} = \frac{c_{A,\text{in}} V_{\text{in}} - c_{A,\text{out}} V_{\text{out}}}{V} = \frac{(c_{A,\text{in}} - c_{A,\text{out}}) V}{18.3 L/s} = 11.9 \text{ gmol/s} \]

Up to now, everything we\'ve done is a repeat of the material balances we learned in Chapter 5. The new step is to equate the \( f_{\text{consumption},A} \) term to the given rate expression times the reactor volume, where \( c_A \) (in the reactor) = \( c_{A,\text{out}} \).

\[ f_{\text{consumption},A} = \left( k_c c_{A,\text{out}} \right) V \]

or

\[ V = \frac{f_{\text{consumption},A}}{k_c c_{A,\text{out}}} \]

So, \( V = \frac{11.9 \text{ gmol/s}}{11.9 \text{ gmol/s}} = 8.800 \text{L} \)

Specifically, we did not assume any previous exposure to calculus. We also assumed only a minimal knowledge of chemistry, such as provided by even a mediocre high-school chemistry class. Finally, while the course requires minimal computer word-processing experience, it does not require prior exposure to computer spreadsheets.

There are several other aspects of the day-to-day operation of the course that may be of interest to the reader. For example, the course includes frequent use of group activities, which serve to hold student interest, increase learning effectiveness, and help first-year students form friendships with one another. In-class quizzes are also used to motivate students to keep up with their learning (a particular problem for many first-year students who developed the habit of last-minute cramming in high school). Classroom demonstrations and examples from everyday life are used to illustrate the chemical engineering principles being discussed. Small pieces of equipment, such as pumps and heat exchangers, are partially disassembled and passed around during class for students to examine; photographs of larger equipment items are also used.

Outside the classroom, we assign reading questions to be answered for each new reading assignment before the mate-
rial is discussed in class, and we assign homework problems for the material after it has been discussed in class. Other course features include the case study, which has already been described, two mid-term examinations, and a final exam. Grading is performed according to predefined criteria in order to encourage cooperation between students.

As mentioned previously, this introductory experience is completed in a two-credit-hour one-semester course. Thus, the resources expended are relatively minimal, while our experience indicates that the benefit derived is significant.

RESULTS

We have now taught the course for four years, and student response has been very positive. At the end of every semester, all courses in our department are subjected to a student evaluation questionnaire, which includes numerical scores to specific questions and the opportunity for students to make unrestricted comments. The numerical scores for the introductory course have consistently corresponded to an overall rating of "excellent" and are among the highest in the department. We also send a questionnaire to all students who change their major from chemical engineering to another discipline. The comments from both of these types of questionnaires, along with feedback during informal conversations, indicate that students feel they have a much better understanding of and appreciation for chemical engineering after having taken the course. Some comments from those surveys are:

- "The course gave me a good idea of what to expect in my major."
- "The course is much more applicable to a business or real-life situation than any course I have taken."
- "The course was EXTREMELY helpful in my decision to stay with ChemE as my major."
- "The course has given me a good idea of what Chemical Engineering is about."
- "I really enjoy this course. If it were up to my chemistry class, I would drop out of ChemE. But this course shows the light at the end of the tunnel."
- "Good prep (sic) for my major, applies concepts and possible real life situations, but not too far over our heads."
- "ChE 170 [was a] good class—I just knew after that one that I didn’t belong."
- "I enjoyed ChE 170, but I wouldn’t like to do it for a career."

In some cases, that knowledge has resulted in students changing majors to something other than chemical engineering. That decision is judged to be positive if made with adequate knowledge and experience.

The course appears to have slightly increased the overall retention of students in the chemical engineering program, but that is difficult to verify at this time. The difficulty arises because approximately 80% of the first-year students in our program leave the university after the first semester or after the first year to serve a two-year mission for the Church of Jesus Christ of Latter-Day Saints. Some of those students take our introductory course before leaving, while others take it after returning. Those students who took the first-year course in the last three years and then began serving their missions have not yet returned for a full year of school, so we are not able to determine if they will continue in the program.

Where there are complete data, we have examined retention as defined by the percentage of first-year students who eventually, but not simultaneously, took the subsequent course in our program (our sophomore course in material and energy balances). During the five years before implementation of our course, freshmen took FORTRAN programming as the first-year course, and 40% eventually took the sophomore class. During the last four years, the new course has been offered in both the first semester (enrollments ranging from 86 to 105) and the second semester (enrollments ranging from 47 to 76). For students who took the introductory course during the first of those years, the retention was higher, at 46%. We will continue to compile retention data as they become available. We feel, however, that changes in overall retention are less important than, and may not be a good indicator for, the increased ability of first-year students to intelligently decide if chemical engineering is a good field for them (one of our main goals).

In addition to providing an overview of chemical engineering, students felt that the introductory course helped prepare them for future courses, particularly the course on material and energy balances normally taken by sophomores. This opinion was consistent with that of the course instructor for the sophomore course, who observed that the students who had taken the introductory course were better prepared than previous students. The instructor also noted that the students had a significantly broader knowledge of the discipline. For example, when he mentioned to the students in the class that phase equilibrium would be important in separation processes such as distillation, they recognized the processes to which he was referring and appreciated the significance of his statement.

Although a quantitative evaluation is difficult, other anecdotal information provides positive feedback about the course. For example, two students who had recently completed the introductory course requested help from one of the authors to explore an issue in process control for use in a paper for a technical writing class. Specifically, they wanted to explore differences between feedback and feedforward control strategies. The students were in the first semester of their third year, a full year before they were scheduled to take our senior-level process control class. Prior to the time we began teaching the introductory course, students at the same point in their education had little, if any, concept of process con-
trol. Yet, these students had learned enough in the introductory course to define a question and pursue the topic further on their own. Incidentally, they were supplied with a process simulation program (PILES) and were able to use the program to address the issues of interest.

It has also been our perception that the course has served to help build relationships between students. They appear to be working in groups and helping each other much more than they did previously. This interaction is facilitated by the group work required as part of the class. Also, grading is structured so that students do not perceive that they are hurting their own grade by helping their classmates. Interaction between the faculty member teaching the course and the students has also been very positive. In many cases this has resulted in continued interaction and discussions, exchange of e-mail, sharing of wedding announcements, etc., long after the final exam is taken.

In order to provide the desired integrated overview, it was necessary to cover a broad variety of chemical engineering concepts. We were concerned that in doing this we might overwhelm the students with too much material. Like most schools, our target for work outside of class (reading and homework problems) is two hours outside class per one hour inside. For a two-credit class (two hours per week in class), this translates to four hours per week outside of class. A recent polling of all our students concerning the time they spend in class work outside of class indicated that the workload for the introductory course was on target at an average of approximately 3-4 hours a week. We conclude from this that the students have not been overwhelmed by the material presented in class.

Finally, the written material for the course has evolved considerably over the past four years, but has now stabilized to a large extent. As mentioned previously, we have recently published a textbook for the course that is available for others who may be interested.

We end this section by noting that the course described in this paper has an appeal that extends to other situations where beginning students need to know about chemical engineering. For example, some colleges have a common freshman engineering course, and the chemical engineering departments do not see the students until the sophomore year. In those cases, the course described here could be given to first-semester sophomores prior to the traditional course on material and energy balances. It could also be used in two-year colleges from which students may transfer into our programs.

CONCLUSION

A new introductory course has been developed for first-year students interested in chemical engineering. This two-credit-hour one-semester course is designed to provide a broad overview of the chemical engineering discipline and a foundation for other courses in the curriculum. Other objectives for the course include the introduction of fundamental principles related to chemical engineering, connection of material to the students' experiences and future coursework, introduction of design concepts, and development of student/faculty and student/student relationships. Student feedback, although qualitative, indicates that the course has been largely successful in accomplishing these objectives.

The laying of a broad introductory foundation at the beginning of a long academic program was of particular interest and importance. Consequently, the course was designed to establish the framework for the rest of the curriculum. Our intention was to facilitate learning by providing an overview and establishing connections so that in-depth material from upper-division courses could readily be integrated into an existing framework, rather than waiting until a senior capstone course to attempt to tie things together. The approach also facilitates learning through repetition by providing a first-year exposure prior to the more-in-depth upper-division exposure.

We are providing this information so that other schools may consider this approach for adoption into their programs. Universities with no freshman engineering course may consider adding a course like the one described here. Schools with an existing general freshman engineering course might consider replacing it with this course for students who are seriously considering chemical engineering as a major. Where this is not possible, this course might be offered to sophomores in chemical engineering. In addition, two-year colleges might use this course to prepare their students for transferring to four-year chemical engineering programs.

We are anxious to receive impressions and suggestions from others who have seen our course or book, or who have experience with similar attempts to prepare first-year students for this discipline.

REFERENCES


2. Cooper, D.J., PICLES (Process Identification and Control Loop Explorer System), Version 4.1, Department of Chemical Engineering, University of Connecticut (1995)
FRESHMAN DESIGN PROJECTS
In the Environmental Health and Safety Department

RONALD J. WILLEY, JOHN M. PRICE
Northeastern University • Boston, MA 02115

Freshmen usually come to us without an engineering background. They are accustomed to working alone on small, well-structured problems, do not understand the laws of thermodynamics, and have little conception about conservation of momentum, energy, and mass. Consequently, we have been reluctant to give open-ended design problems to them in spite of the fact that the fun of engineering is working on real problems and finding solutions to them. It seems too big of a risk.

While incorporating engineering health and safety issues into the engineering curriculum is desirable and has been addressed by ABET,[1] meeting this major challenge is difficult given the many other ABET requirements. Past papers that address possible approaches include the work of Gute, et al.,[2] Bethea,[3] and Rossignol, et al.[4] Our approach introduces students to open-ended problems early in the curriculum. We find that their creative abilities provide fresh solutions to mundane problems.

FRESHMAN CURRICULUM
Northeastern University has a five-year cooperative education program in engineering. The freshman year has three quarters, and upperclassmen take two quarters of classes and of cooperative education during each of the next four years. The result is eleven quarters of classroom training and seven or eight quarters of industrial experience.

To allow freshmen the opportunity to meet College of Engineering (COE) faculty early in their academic career, COE faculty take an active role with freshman engineering students. Engineering courses offered in the freshman year are

• C-programming during the fall
• Problem solving using spreadsheets and MathCad in the winter
• Engineering design in the spring

The engineering design course is divided into ten sections, with about thirty students in each section. The sections meet for 65 minutes three times a week. Our quarter system allows for just under eleven weeks of classroom meetings each quarter. Sections are divided by intended major and assigned to faculty from the appropriate departments. This paper is devoted to declared chemical engineering majors.

Engineering design uses a textbook developed by Northeastern’s Gerald Voland, Engineering by Design.[5] He breaks down the design process into key stages that include

1) Needs determination
2) Design goals and specifications
3) Abstraction
4) Evaluation of alternative designs
5) Ergonomic analysis

In general, engineering design students are assigned a minor...
TABLE 1
Proposal Outline for Student Project Design Submittal

GE1103 • Spring 1996
Minor Design Project • Due April 23, 1996
"If there isn’t a need why bother?" R.J. Willey 4/5/96

Summary:
Excellent designs begin with a proper needs assessment and the correct statement of the problems to be solved. An excellent example of posing the proper questions before solving the problem at hand is space craft reentry. Your group is to prepare a 5-page proposal (double spaced and 12-point Courier font) and a 5-minute presentation about your major design project. This work will be due on April 23, 1996. Mr. Jack Price will review and assign grades on your oral presentations (25% of the total minor design project grade). Each group must go to the front of the classroom. After a brief introduction from each group member, one of your group members should serve as a spokesperson. That person should briefly define the need, the problem to be solved, and the methods to be used.

Proposal Outline
Objectives
Using a numbered list, state your objectives. Be as precise as possible.

Background
Who will be served by your solution/design? Where will your solution/design be used? What is the past history related to the problem? Are there any important references related to the problem that you are working on? Existing solutions and prior work on the problem should be described.

Methodology
Focus on what techniques you will use to help you solve the "problems" and succeed with a successful design. Use Prof. Voland’s and class notes to obtain methods on how to proceed.

Proposed Schedule
Include a proposed schedule that is similar to the schedule shown in Figure 2.6, page 88. Use weeks as the time period and adjust phases to match your problem/design.

Person Loading Chart
Include a person loading (Gantt) chart like the one shown in Figure 2.7. Use hours as the time period and adjust the task list to match your problem/design requirement.

Autocad Drawing
Include a schematic or layout drawing for the project that you are working on.

Expected Results
Begin with the end in mind. What are the "deliverables"? Who will benefit?

Costs
What will be the costs involved? "Personpower" can be estimated at a direct cost of $45.00/hr. Other costs will involve materials and supplies to bring about the solution/design (not the cost of the final recommended design).

TABLE 2
Major Design Projects, Spring 1996

<table>
<thead>
<tr>
<th>#</th>
<th>Department</th>
<th>Location</th>
<th>Contact</th>
<th>Project Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mail Services</td>
<td>Basement</td>
<td>J. Devine</td>
<td>Workstation lighting evaluation</td>
</tr>
<tr>
<td>2</td>
<td>Mail Services</td>
<td>Basement, Columbus Pl.</td>
<td>J. Devine</td>
<td>Noise level survey for letter-stamping machine</td>
</tr>
<tr>
<td>3</td>
<td>Physical Plant</td>
<td>Mail room, Columbus Pl.</td>
<td>J. Devine</td>
<td>Employee fall protection from loading docks</td>
</tr>
<tr>
<td>4</td>
<td>Physical Plant</td>
<td>Various</td>
<td>B. Mitcheson</td>
<td>Loading-dock assessment</td>
</tr>
<tr>
<td>5</td>
<td>Environment Health</td>
<td>Various laboratories</td>
<td>S. Brehio</td>
<td>Quality control check on safety showers and eye-wash station survey</td>
</tr>
<tr>
<td>6</td>
<td>Environment Health</td>
<td>Various dark rooms</td>
<td>S. Brehio</td>
<td>Evaluation of silver recovery options for environmental compliance</td>
</tr>
<tr>
<td>7</td>
<td>Environment Health</td>
<td>Various computer labs</td>
<td>J. Price</td>
<td>Ergonomic evaluation of computer workstations</td>
</tr>
<tr>
<td>8</td>
<td>Environment Health</td>
<td>Various laboratories</td>
<td>S. Brehio</td>
<td>Opportunities for waste minimization in the generation of HPLC solvent waste</td>
</tr>
<tr>
<td>9</td>
<td>Environment Health</td>
<td>Various laboratories</td>
<td>S. Brehio</td>
<td>Strategies, facility requirements, and costs for a central organic solvent bulk- ing facility</td>
</tr>
<tr>
<td>10</td>
<td>Chemical Engineering</td>
<td>8 Mugar</td>
<td>A. Bina</td>
<td>Design of flow measurement experiment</td>
</tr>
</tbody>
</table>

and a major design project, each to be completed using the methods presented in Voland’s text. In the chemical engineering section, these minor and major projects address the same problem. Our minor design project (see Table 1) consists of a needs assessment and proposed approach to one of the major design projects listed in Table 2. The major design project is execution of the actual work proposed.

Students are divided into groups of three at the second class meeting, providing a total of ten teams. Each team selects a project from Table 2—no duplication is allowed. Each team’s interests are matched to a project.

Each project assigned to a team has a University administrator who serves as the “client.” The student teams serve as consulting engineering services. Additionally, our Office of Environmental Health and Safety (OEHS) serves as a mentor and an interface between the clients and the consultants.

As Table 2 shows, design projects vary from noise surveys in the University mail room to the optimization of hazardous waste disposal. The projects introduce students to survey instruments, to data evaluation, to regulatory compliance issues, and involve interaction with a variety of people. Students begin learning engineering principles (e.g., velocity measurements involving Bernoulli’s equation), team skills, communication skills (written and oral), and economics. With a little investment and some oversight by the OEHS, the University benefits from the students’ project recommendations (discussed in more detail below).

The minor and major assignments, the proposal, and the design solution comprise 55% of the course grade. The remaining portion is based on two examinations (30%) and daily homework assignments.
(15%). AutoCad is also presented in this class (about one third of the lectures), and students are encouraged to make drawings of their major assignment using it.

As with any open-ended term project, students tend to put off work until the last minute, with the usual disastrous results. To avoid this outcome, students are required to submit a weekly log book and are given small assignments that push them 1) to get their groups together, 2) to begin meeting with their contacts, 3) to obtain background information, and 4) to work towards a solution. The logbook system also serves to identify early such problems as an inability to connect with the University contact or the existence of a nonparticipating member.

For the instructor, the project process is similar to managing a small consulting firm made up of all “rookie” teams. The students generally find their contacts during the first week and will begin the literature checks, but then their methods diverge. One year, two seniors were intentionally recruited to work with two freshman team members. With the advantage of the seniors’ co-op and military experience, the teams attacked their project with vigor. Both designs solutions—the redesign of a loading-dock area and the creation of a safety checklist (see Table 3)—are now being implemented by the University.

Eight of the ten groups functioned well. Their final designs were quite good. They succeeded, in part, because they were self-selecting and they shared a general interest in working on a real problem.

On the other hand, one of the eight all-freshman teams was not successful. No previous engineering work experience or effective leadership existed within the group. One student made his initial contact with the client regarding the design of a flow measurement system for two centrifugal pumps. He quickly assessed the situation, claimed the solution was easy, and stated that he should be done after just a few hours of work. He never included the other team members in the plans or their execution and they, in turn, never tried to participate, expecting this student to carry them through.

Other all-freshman teams turned in good-to-excellent reports. One team worked the mail room workstation lighting problem. As part of their presentation, they built a 3-D model of the room. The model ceiling had holes cut out at the

### TABLE 3

<table>
<thead>
<tr>
<th>Loading Dock Safety Checklist Generated by Students Who Worked on Project #3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pnts</strong></td>
</tr>
<tr>
<td>3 _yes _ no</td>
</tr>
<tr>
<td>3 _yes _ no</td>
</tr>
<tr>
<td>1 _yes _ no</td>
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<tr>
<td>1 _yes _ no</td>
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<td>1 _yes _ no</td>
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<td>1 _yes _ no</td>
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<td>1 _yes _ no</td>
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<tr>
<td>3 _yes _ no</td>
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<td>3 _yes _ no</td>
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<td>3 _yes _ no</td>
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<td>1 _yes _ no</td>
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<tr>
<td>3 _yes _ no</td>
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<tr>
<td>2 _yes _ no</td>
</tr>
<tr>
<td>1 _yes _ no</td>
</tr>
<tr>
<td>2 _yes _ no</td>
</tr>
<tr>
<td>2 _yes _ no</td>
</tr>
</tbody>
</table>

The above checklist is based on a ranking system of 1 to 3 points per question. A (3) is deemed critical, a (2) is deemed important, while a (1) is deemed optional. To find your total possible score, add the possible points column, disregarding those questions that are non-applicable. For each question answered “yes,” give yourself the point amount given to that question. For each question answered “no,” add no points. Add all your scored points. This will give you your total raw score. Now review your total raw score and make sure it complies with the following:

All the questions given a rank of (3) are answered “yes.”
At least 80% of the questions given a rank of (2) are answered “yes.”
Questions with a ranking of (1) are left to the discretion of the proper management.
If these compliances have been met, then your dock is in accordance with the safety measures we require. If this is not so, then adjustments and modifications must be made until the requirements are met.
existing lighting-fixture locations, and using a simple flashlight shining from above, the students were able to demonstrate the inefficiencies of the lighting grid. They then demonstrated how the placement of two additional lighting fixtures over the proper work area could correct the lighting. By exchanging the top of the 3-D model with the properly modified ceiling and shining the light through it, they were able to present their solution efficiently and observably.

Since students have generally been conditioned to work individually prior to entering college, one of our biggest challenges was getting them to work together. While team work is a novelty in the academic environment, when these students take on their first industrial co-op assignment, team work is often the expected mode of operation. An important feature of our approach is to develop team-working skills.

Another related challenge was the division of work. While eight of the ten student teams handled the division of work quite well, in one team there was one student overly concerned about the “grade” and another more concerned about what he was “really learning.” These two never reached a consensus about what the professor wanted and ended up giving individual solutions. Meanwhile, the group’s third member watched in bewilderment while the other two argued constantly during team meetings.

Another poorly functioning group had a clear cultural divergence that led to little or no team effort. This group was not self-selecting, having been formed of late registrants who came to class for the first time on the second day. The members were from different countries and did not know each other previously. This team did not work well together primarily because one team member worked on the problem by himself and didn’t include the other two members who, in this case, were satisfied that someone else was going to do the work.

We required two group reports and two presentations during the quarter. The first report was the proposal for the “client’s approval” and was due about midway into the quarter. The corresponding presentations were limited to five minutes per group and were given on the day the proposals were due. The second, formal report described the final design solution intended to meet the client’s needs. The second presentations were twenty minutes each and consisted of a summary of the design solution.

Several models, iconic (resembling the situation but not having the functionality) and analogic (not resembling the situation but having the functionality) were made by the groups as the projects progressed. Figure 1 shows one example of student creativity. The model shower pictured was made to help explain design requirements for American With Disabilities ACT compliance concerns.

Another group built a scale model of a process to recover silver generated in the University’s photo labs. This model was constructed so that each major functional component could be removed. The students used the model during their presentation to help the class understand the functionality of their proposed silver-recovery system. The presentation was extremely rewarding for the class and the instructor.

CONCLUSIONS

Open-ended, real problems are challenging to make work in the classroom. There is no instructor’s solution manual available and each project is demanding, requiring constant attention by the instructor. Project paths can change as the quarter progresses. Common difficult situations center around a contact not responding or a group member not participating. Sometimes, design problems are too vague.

We encourage others to contact their Environmental Health and Safety departments to discuss a similar approach at their University. Not only will their students learn to alleviate persistent campus hazards, their school just might gain some inexpensive physical improvements.

REFERENCES

INNOVATIVE WAYS
OF TEACHING POLYMERIZATION
REACTION ENGINEERING
Exchanging Information Between the University and Industry

JOÃO B. P. SOARES, ALEXANDER PENLIDIS, ARCHIE E. HAMIELEC*
University of Waterloo • Waterloo, Ontario, Canada N2L 3G1

The polymer industry is one of the most important and fastest growing segments of the chemical industry today, and this growth has created a high demand for professionals with adequate knowledge to attend to its very special needs. Besides the classical core subjects of the chemical engineering curriculum, knowledge of several additional topics is required for the student who intends to apply for a position in the polymer manufacturing industry. The technology for polymer manufacture is in a constant state of change, and any undergraduate or graduate program that relies only on established approaches in polymer chemistry and physics will quickly find itself out of date. In this article we will describe how our interaction with several polymer manufacturing companies through industrial short courses and research projects has led to the development of a dynamic and up-to-date undergraduate and graduate curriculum in polymer science and engineering technology.

The technology for polymer production is a very dynamic field due to the high demand for polymeric materials with entirely novel or improved properties. New discoveries and applications in polymerization catalysts and initiators, in polymer reaction engineering, polymer characterization, and polymer processing frequently redefine the boundaries of knowledge in polymer science and technology. As a result, several of the leading technologies for polymer manufacture are constantly being modified to meet new market demands.

Although it is stimulating for those involved in the field, this dynamic pace nonetheless creates a significant concern for instructors teaching polymer-related courses in academia since it requires that both undergraduate and graduate courses be regularly updated to reflect these new developments. Keeping up to date with the scientific literature alone, even

**TABLE 1**
Partial List of Scientific Journals in Polymer Science and Engineering

<table>
<thead>
<tr>
<th>Journal Name (Periodicity)</th>
<th>Publisher</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Polymer Journal (Monthly)</td>
<td>Pergamon Press</td>
</tr>
<tr>
<td>International Polymer Science and Tech. (Monthly)</td>
<td>RAPRA</td>
</tr>
<tr>
<td>Journal of Applied Polymer Science (Quarterly)</td>
<td>John Wiley &amp; Sons</td>
</tr>
<tr>
<td>Journal of Macromolecular Science (Monthly)</td>
<td>Marcel Dekker</td>
</tr>
<tr>
<td>Journal of Polymer Engineering (Quarterly)</td>
<td>Freund Pub. House</td>
</tr>
<tr>
<td>J. of Polymer Sci.: Polym. Chem. (Month/Semi-Month)</td>
<td>Wiley &amp; Sons</td>
</tr>
<tr>
<td>Macromolecules (Bi-Weekly)</td>
<td>American Chem. Soc.</td>
</tr>
<tr>
<td>Macromolecular Reports (8 per Year)</td>
<td>Marcel Dekker</td>
</tr>
<tr>
<td>Macromolecular Symposium (Irregular)</td>
<td>Hüthig &amp; Wepf Verlag</td>
</tr>
<tr>
<td>Polymer (Bi-Weekly)</td>
<td>Elsevier</td>
</tr>
<tr>
<td>Polymer Bulletin (Bi-Monthly)</td>
<td>Springer</td>
</tr>
<tr>
<td>Polymer International (Monthly)</td>
<td>John Wiley &amp; Sons</td>
</tr>
<tr>
<td>Polymer Journal (Monthly)</td>
<td>Soc. of Poly. Sci., Japan</td>
</tr>
<tr>
<td>Polymer Reaction Engineering Journal (Quarterly)</td>
<td>Marcel Dekker</td>
</tr>
<tr>
<td>Progress in Polymer Science (Bi-Monthly)</td>
<td>Pergamon Press</td>
</tr>
<tr>
<td>Trends in Polymer Science (Monthly)</td>
<td>Elsevier</td>
</tr>
</tbody>
</table>

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* McMaster University, Hamilton, Ontario, Canada L8S 4L7

Chemical Engineering Education
in a relatively narrow branch of polymer science and engineering, can be a time-consuming task due to the numerous scientific journals available in the field, some of which are listed in Table 1.

The polymer science and engineering theme illustrates remarkably well the old saying that in order to teach a subject well, one must be actively involved in research in that subject. That is the only way one can stay current with all the new developments and maintain a sense of coherence and relevance in the face of the immense body of information available to academics nowadays.

An additional and equally important point to remember when designing an academic course, especially at the undergraduate level, is that equal importance must be given to both scientific-relevant topics and those that are of immediate concern to industry, since most students will be seeking industrial jobs after graduation. Results from recent surveys on employment in the United States and Europe indicate that as many as 70% of chemical engineering graduates will have worked with a polymer-related industry at some point in their professional career. Unfortunately, the importance of polymer courses for chemical engineers at the undergraduate level is still overlooked in several academic institutions.

In this article, we will describe our instructional efforts in polymer science and technology at three distinct levels: industrial-intensive short courses, academic courses, and final-undergraduate-year design and research projects. We will show how these activities complement each other, leading to university courses with a high content of industrially relevant material and to industrial courses that bring recent academic advances in polymer science and engineering to industrial applications.

**INDUSTRIAL SHORT COURSES**

We offer three courses annually in Canada, the United States, and Europe. Although the details of these courses might vary according to the type of audience they are intended for, they combine a very strong component in fundamental understanding of polymerization reaction engineering with recent advances in several aspects of polymerization processes. In addition to the regular lecturers, invited speakers (mainly from industry, but also from academia) are regularly asked to give two- to four-hour lectures. It has been our experience that the material covered by the invited speakers is highly relevant to our industrial short courses and can be successfully used to complement the content of our university courses.

Table 2 shows the syllabus of a recent industrial intensive short course in polymerization chemistry and engineering with recent advances in several aspects of polymerization processes. In addition to the regular lecturers, invited speakers (mainly from industry, but also from academia) are regularly asked to give two- to four-hour lectures. It has been our experience that the material covered by the invited speakers is highly relevant to our industrial short courses and can be successfully used to complement the content of our university courses.

**TABLE 2**

**Syllabus of Industrial Short Course**

<table>
<thead>
<tr>
<th>Day Sessions</th>
<th>Topics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong> Chain-Growth</td>
<td>• Linear, branched, and crosslinked chains via free-radical polymerization</td>
</tr>
<tr>
<td>Polymerization</td>
<td>• Linear and branched chains via ionic mechanisms (Ziegler-Natta and Metallocenes)</td>
</tr>
<tr>
<td>Mechanisms and Kinetics</td>
<td>• Stockmayer's bivariate distribution—instantaneous property methods</td>
</tr>
<tr>
<td><strong>Advanced Polymerization</strong></td>
<td>• Identification of multiple active site types (GPC, TREF, NMR)</td>
</tr>
<tr>
<td>Kinetics</td>
<td>• Identification of active site performance</td>
</tr>
<tr>
<td></td>
<td>• Long chain branching</td>
</tr>
<tr>
<td></td>
<td>• Ziegler-Natta and metalloocene catalysis</td>
</tr>
<tr>
<td><strong>2</strong> Emulsion, Dispersion, and Suspension Processes</td>
<td>• Styrenics, PVC</td>
</tr>
<tr>
<td>Polyolefinic Processes</td>
<td>• Batch, semi-batch, and continuous operation</td>
</tr>
<tr>
<td></td>
<td>• Thermodynamics and surface chemistry</td>
</tr>
<tr>
<td></td>
<td>• Particle nucleation and growth</td>
</tr>
<tr>
<td></td>
<td>• Ionic and steric stabilization</td>
</tr>
<tr>
<td></td>
<td>• Particle size distribution and molecular weight distribution</td>
</tr>
<tr>
<td></td>
<td>• Molecular, rheological, and solid-state properties (LDPE, HDPE, LLDPE, PP; impact copolymers)</td>
</tr>
<tr>
<td></td>
<td>• Effect of short and long chain branching and molecular weight distributions</td>
</tr>
<tr>
<td></td>
<td>• Effects of main process variables on productivity and polymer properties</td>
</tr>
<tr>
<td></td>
<td>• Models of polyolefin production processes and plant data comparisons</td>
</tr>
<tr>
<td><strong>3</strong> Principles of Polymer Reactor Modeling and Kinetic Data Collection</td>
<td>• Batch, semi-batch, and continuous operation</td>
</tr>
<tr>
<td></td>
<td>• Dynamic modeling of reactor systems</td>
</tr>
<tr>
<td></td>
<td>• Population balance equations for particle size and molecular weight</td>
</tr>
<tr>
<td></td>
<td>• Screening and factorial designs for data collection</td>
</tr>
<tr>
<td></td>
<td>• Sequential and non-linear design of experiments</td>
</tr>
<tr>
<td></td>
<td>• Evolutionary operation</td>
</tr>
<tr>
<td></td>
<td>• Model discrimination issues</td>
</tr>
<tr>
<td><strong>4</strong> Modern Special Topics</td>
<td>• Bulk, solution, and emulsion terpolymerizations</td>
</tr>
<tr>
<td></td>
<td>• Reactivity ratio estimation</td>
</tr>
<tr>
<td></td>
<td>• Monte Carlo methodology and applications</td>
</tr>
<tr>
<td></td>
<td>• Reactivity ratio estimation</td>
</tr>
<tr>
<td></td>
<td>• Optimal sensor selection</td>
</tr>
<tr>
<td></td>
<td>• Reactive processing</td>
</tr>
<tr>
<td></td>
<td>• Principles of temperature rising elution fractionation (TREF)</td>
</tr>
<tr>
<td></td>
<td>• Measurement of long chain branching (GPC/VISC/LALLS)</td>
</tr>
<tr>
<td></td>
<td>• Chemical modification of polymers</td>
</tr>
<tr>
<td></td>
<td>• Crystallization Analysis Fractionation (CRYSTAF)</td>
</tr>
<tr>
<td></td>
<td>• Definitions of rubbers and elastomers</td>
</tr>
<tr>
<td></td>
<td>• Synthesis and production of rubbers</td>
</tr>
<tr>
<td></td>
<td>• Recent developments in EP(D/M and poly-α-olefins: metalloocene catalysis/gas phase process/single site vs. multi-site catalysts</td>
</tr>
<tr>
<td></td>
<td>• Molecular structure and physical properties</td>
</tr>
<tr>
<td></td>
<td>• Compounding, vulcanization, and applications</td>
</tr>
<tr>
<td><strong>5</strong> Monitoring, Dynamics, and Control of Polymerization Reactors</td>
<td>• Overview of current control practices</td>
</tr>
<tr>
<td></td>
<td>• Sensors for monitoring reactor behavior</td>
</tr>
<tr>
<td></td>
<td>• Energy balance and rate control</td>
</tr>
<tr>
<td></td>
<td>• Control of product properties</td>
</tr>
<tr>
<td></td>
<td>• Model use to combine on-line and off-line data</td>
</tr>
<tr>
<td></td>
<td>• Kalman filtering and inferential control</td>
</tr>
<tr>
<td></td>
<td>• Software sensors and multivariable statistics</td>
</tr>
<tr>
<td></td>
<td>• Optimal reactor grade changes</td>
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<td></td>
<td>• Advanced linear and nonlinear control</td>
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</tbody>
</table>
reaction engineering, with emphasis on metalloocene catalysts, emulsion, and suspension polymerization processes. As can be seen, the first three sessions concentrate on fundamentals and mathematical modeling of coordination and free-radical polymerization. This forms the basis for understanding of the more applied topics covered in subsequent sessions.

Properties of polyolefin resins and rubbers, especially structure-property relationships, are given special attention. Recent advances on reactor monitoring, dynamics, and control, as well as kinetic data collection and analysis, are also covered in depth.

A session on modern special topics is generally offered to cover new technologies and research topics in polymer science and engineering. Modern polymer characterization techniques are generally covered in the last session, although they are discussed at every available opportunity during the previous sessions, including applications of on-line sensors.

As mentioned before, invited speakers make an important contribution to this instructional effort. Table 3 lists the names, topics, and affiliations of some of the invited speakers who have participated in our courses in the past five years.

In-house short courses are also offered to meet the needs of specific companies. These in-house courses may range from one to five days. They can be as general as the course described in Table 2 or focused on the technologies of the specific company. Possibilities also include combinations of special topics: for example, a two-day update on the use of statistical methods and the design of experiments for polymerization processes. Table 4 shows the syllabus of such a course on polymer reaction engineering of polyolefinic processes recently given in the United States. This particular course concentrated on the manufacture of polyolefins, with special emphasis on new technologies for metallocene catalysts.

It has been our experience that these courses are mutually beneficial for the industrial participants and for the lecturers. On one hand, the industrial participants have an opportunity to update their knowledge of modern advances in a broad area of polymer science and technology, and over the years we have been glad to note that several industrial participants have initiated research collaborations with the instructors after taking the courses and that some of the topics introduced

### Table 3

<table>
<thead>
<tr>
<th>Invited Speakers</th>
<th>Topics</th>
<th>Affiliations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. T.A. Duever</td>
<td>Design of experiments for polymerization data collection</td>
<td>Chem. Eng. Department, University of Waterloo</td>
</tr>
<tr>
<td>Dr. G.N. Foster</td>
<td>Characterization and physical properties of polyolefins</td>
<td>Union Carbide, Bound Brook, CT</td>
</tr>
<tr>
<td>Dr. E. Kontos</td>
<td>Rubber manufacturing processes and product characterization</td>
<td>Uniroyal Chem. Co., Naugatuck, CT</td>
</tr>
<tr>
<td>Dr. K. Malone</td>
<td>Organic peroxides for free-radical polymerization</td>
<td>Elf Atochem., Buffalo, NY</td>
</tr>
<tr>
<td>Dr. B. Monrabal</td>
<td>Crystallization analysis fractionation (CRYSTAF)</td>
<td>Polymer Character., S.A., Patera, Spain</td>
</tr>
<tr>
<td>Dr. G.L. Rempel</td>
<td>Metallocene catalysis and catalytic modification of polymers</td>
<td>Chem. Eng. Department, University of Waterloo</td>
</tr>
<tr>
<td>Dr. C. Tzoganakis</td>
<td>Polymer processing and reactive extrusion</td>
<td>Chem. Eng. Department, University of Waterloo</td>
</tr>
</tbody>
</table>

### Table 4

| Syllabus: In-House Short Course for Polyolefin Production and Characterization |
|--------------------------------------|--------------------------------------------------------------------------------|
| Introduction                         | • Soluble vs. heterogeneous catalysts<br>• Polymerization mechanisms: homo- vs. copolymerization/linear<br>• Control of stereoregularity, molecular weight, short and long chain branching<br>• Effect of polymer microstructure on mechanical and rheological properties |
| Polymerization Processes             | • Gas phase/slurry bulk monomer and diluent/solution<br>• Fluidized bed vs. stirred bed gas-phase reactors<br>• Loop reactors vs. stirred-bed slurry reactors<br>• Processes for manufacture of high-impact copolymers<br>• Vis-breaking processes |
| Basic Mathematical Modeling Techniques | • Mass balances: batch, semi-batch, and continuous operation of CSTRs and CSTR trains<br>• Energy balance |
| Advanced Mathematical Modeling of Polymerization Processes | • Polymerization kinetics<br>• Population balances<br>• Instantaneous properties methods vs. method of moments<br>• Multiplicity of active sites<br>• Heat and mass transfer limitations<br>• Particle size distribution |
| Catalytic Site Type Identification C     | • Deconvolution of GPC curves using Flory’s most probable distribution<br>• Deconvolution of TREF curves using Stockmayer’s distribution<br>• GPC/LC-transform—a new approach to site identification<br>• CRYSTAF and CITREF |
| Reactor Dynamics/Control/Grade Transitions | • Overview of current control practices<br>• Sensors for monitoring reactor behavior<br>• Energy balance and rate control<br>• Control of product properties<br>• Model use to combine on-line and off-line data<br>• Kalman filtering and inferential control<br>• Software sensors and multivariable statistics<br>• Optimal reactor grade changes<br>• Advanced linear and nonlinear control |
The technology for polymer manufacture is in a constant state of change, and any undergraduate or graduate program that relies only on established approaches in polymer chemistry and physics will quickly find itself out of date. In this article we will describe how our interaction with several polymer manufacturing companies . . . has led to the development of a dynamic and up-to-date undergraduate and graduate curriculum in polymer science and engineering technology.

### TABLE 5
Syllabus for Polymer Reaction Engineering Course

<table>
<thead>
<tr>
<th>Week</th>
<th>Topics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Overall course objectives • Basic concepts and definitions in polymer science</td>
</tr>
<tr>
<td>2</td>
<td>Definition of molecular weight averages and distributions • Method of moments • Analytical techniques for measuring molecular weights</td>
</tr>
<tr>
<td>3</td>
<td>Step growth polymerization • Condensation vs. addition polymers • Statistical treatment of step-growth polymerization • Equal reactivity assumption (ERA) • Irreversible growth with ERA • Carothers equation • Flory-Shultz distribution • Determination of kinetic constants</td>
</tr>
<tr>
<td>4</td>
<td>Stoichiometry of linear systems • Generalized Carothers equation • Deterministic treatment of step-growth polymerization • Modeling step-growth polymerization without ERA • Effect of monofunctional agents • Reversibility and interchange reactions</td>
</tr>
<tr>
<td>5</td>
<td>Free-radical homo- and copolymerization • Initiation, propagation, and termination • Basic hypotheses • Commercial initiators • Initiation rate • Isothermal operation • Initiator efficiency • Propagation characteristics</td>
</tr>
<tr>
<td>6</td>
<td>Chain conformations • Tacticity • Termination characteristics • Choice and amount of initiator • Inhibition and retardation • Impurities • Development of equations for polymerization production rate • Homopolymerization in batch reactors • Dead-end polymerization</td>
</tr>
<tr>
<td>7</td>
<td>Derivation of the instantaneous copolymer composition (ICC) equation • Plots of the ICC equation • Reactivity ratios • Introduction to composition control methods • Meyer-Loeser equation • Cumulative copolymer composition • Depropagation • Molecular weight (MW) development for linear homopolymers</td>
</tr>
<tr>
<td></td>
<td><strong>Mid-Term Exam</strong></td>
</tr>
<tr>
<td>8</td>
<td>MW development: averages and distributions • Practical hints on MW control and temperature programming • Energy balances • Temperature and controller design • Modes of termination • Reactions with chain transfer agent • Chain transfer to monomer • MW development: branched homopolymers</td>
</tr>
<tr>
<td>9</td>
<td>Transfer to polymer • Terminal double-bond and internal double-bond reactions • Backbiting • Industrial examples • Method of moments for branched systems • MW development for linear and branched copolymers • Effect on glass transition temperature • Bimolecular termination kinetics</td>
</tr>
<tr>
<td>10</td>
<td>Emulsion polymerization: contrast with other polymerization methods • Nucleation and growth • Thermodynamics • Free-radical concentration • Emulsion polymerization kinetics: homo- and copolymerization</td>
</tr>
<tr>
<td>11</td>
<td>Latex particles size • Polymer molecular weight • Effects of pH and ionic strength • Impurities • Coagulation • Multiple phase latex particles • Introduction to mathematical and computer modeling</td>
</tr>
<tr>
<td>12</td>
<td>Ionic (anionic and cationic) and coordination (Ziegler-Natta and metallocene) polymerizations • Brief overview • Mechanisms • Polymer properties</td>
</tr>
<tr>
<td>13</td>
<td>Review • Sample problems and general discussion on the design of large polymerization reactors</td>
</tr>
<tr>
<td></td>
<td><strong>Final Exam</strong></td>
</tr>
</tbody>
</table>

**UNDERGRADUATE COURSE**

Table 5 presents the syllabus of the introductory polymer course given in the Chemical Engineering Department at the University of Waterloo. It is offered annually (6 hours per week) as a technical elective course for senior undergraduate students and as an introductory course for graduate students who are pursuing MASc and PhD degrees in polymer science and engineering.

This course covers the main areas of polymer reaction engineering for step-growth and chain-growth polymerization. Special emphasis is put on understanding fundamental polymerization principles, using both experimental polymerization data and mathematical modeling techniques. The statistical nature of polymerization is examined in detail together with the concepts of molecular weight and chemical composition distribution in polymers. Polymer characterization techniques are introduced as tools to correlate polymer chain structure to polymerization mechanisms and processes. Several modern polymerization processes (free-radical emulsion, suspension, and solution, as well as Ziegler-Natta and metalloocene-catalyzed processes) are presented to illustrate the fundamental concepts covered in the initial part of the course. The experience gained by our interaction with industry via collaborative research projects and short courses helps us identify the most relevant during the courses have found practical applications in industry. On the other hand, the instructors benefit greatly from these interactions since the contacts permit them to stay “in tune” with the current needs of industry and with recent advances of a practical nature that very often are not disclosed in the scientific literature. This is not only a good way of influencing the direction of some of our applied research, but also an excellent way of covering current trends of the polymer industry in our university courses. Our students enjoy, and benefit tremendously from, a knowledge of these current industrial trends.
polymerization processes for this section of the course. In this way, it has been possible to design a course with a strong industry-oriented component while at the same time maintaining a high level of scientific and academic content.

The course components consist of bi-weekly assignments, a mid-term exam, and a final exam. Graduate students are also required to work on a project, results from which are presented orally at the end of the course. Table 6 shows a selective list of required and supplementary references for the course. In addition to these references, several technical articles describing the state-of-the-art in polymerization reaction engineering are given to the students as recommended reading throughout the course.

In order to familiarize students with the vast amount of literature available in polymer science and engineering, online literature searches are also conducted during the course in collaboration with our library personnel. Computer simulation case studies in polymerization reaction engineering are also done using WATPOLY, a user-friendly package developed at Waterloo for the dynamic simulation of solution, emulsion, and suspension polymerization reactors. In this way, several complex aspects of these polymerization systems can be examined by the students without the need of tedious and time-consuming calculations.

Additionally, the course is complemented with a tour to the polymerization pilot plant facilities of the department and with site visits to polymer manufacturing and processing companies in the region.

Samples of polymer reaction engineering-related problems (tests or assignments) that have arisen from our industrial interactions are presented in Table 7. Some of these problems are open-ended and may have multiple solutions. They are an extremely powerful vehicle in giving the students a flavor of "real-world polymer production" problems.

SENIOR-YEAR DESIGN/RESEARCH PROJECTS

All fourth-year undergraduate students have to complete either an individual research or design project or a group process design project in direct collaboration with one faculty member. Several Canadian and American companies sponsor these projects. Our interaction with polymer manufacturing companies has been beneficial in defining polymer-related research and design projects. Some of these projects are described in Table 8.

CLOSING REMARKS

University-industry interaction via industrial short courses and collaborative research projects can bring several advantages to both academic and industrial participants. As a result of our own experience with short courses, we have been able to design academic courses with a high content of industrially relevant material. Instead of jeopardizing the academic and fundamental content of these undergraduate and graduate courses, this approach has actually stimulated the students to better understand the mechanistic and fundamental aspects of polymerization processes that have prominent application in both academia and industry.

On the other hand, industrial short courses that bring recent fundamental scientific advances to industrial applications have helped clarify or show different solution alterna-

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**TABLE 6**

Textbook and Supplementary Reading

- Allcock and Lampe • *Contemporary Polymer Chemistry*, 2nd ed. • Prentice Hall (1990)
- Bicerano • *Prediction of Polymer Properties* • Marcel Dekker (1993)
- Billingham • *Molar Mass Measurements in Polymer Science* • Kogan Page Ltd. (1977)
- Billmeyer • *Textbook of Polymer Science* • Interscience (1984)
- Brandrup and Immergut • *Polymer Handbook* • John Wiley & Sons (1975)
- Several authors • *Comprehensive Polymer Science*, 7 volumes • Pergamon Press (1988)
- Flory • *Principles of Polymer Chemistry* • Cornell University Press (1953)
- Grukev • *Polymer Process Engineering* • Prentice Hall (1994)
- Gupta and Kumar • *Reaction Engineering of Step Growth Polymerization* • Plenum Press (1987)
- Ham • *Vinyl Polymerization* • Marcel Dekker (1967)
- Hiemenz • *Polymer Chemistry: The Basic Concepts* • Marcel Dekker (1984)
- McCrum, Buckley, Bucknall • *Principles of Polymer Engineering* • Oxford University Press (1988)
- Peebles • *Molecular Weight Distribution in Polymers* • Interscience (1971)
- Rabek • *Experimental Methods in Polymer Chemistry* • John Wiley & Sons (1980)
- Rempp and Merrill • *Polymer Synthesis* • Huthig/Wepf Verlag (1986)
- Rosen • *Fundamental Principles of Polymeric Materials* • John Wiley & Sons (1993)
- Rudin • *The Elements of Polymer Science and Engineering* • Academic Press (1982)
- Saunders • *Organic Polymer Chemistry* • Chapman and Hall (1988)
- Sperling • *Introduction to Physical Polymer Science*, 2nd ed. • John Wiley & Sons (1992)
- van Krevelen • *Properties of Polymers* • Elsevier (1990)

*Chemical Engineering Education*
TABLE 7
Polymer Reaction Engineering Problems
Assignments and Exams

PROBLEM 1: Given the following data, calculate (a) the instantaneous number average chain length of the polymer, and (b) the average lifetime of a growing chain. Neglect chain transfer and assume that termination is by disproportionation only.

DATA: \( k_0 = 900 \text{ L/mol.s} \); \( k_p^1 = 3 \times 10^{-3} \text{ s}^{-1} \); \( k_p^0 = 0.017 \text{ mol/L} \); \( M_p = 1.5 \text{ mol/L} \); \( p_M = 0.91 \text{ g/cm}^3 \)

PROBLEM 2: MMA is being polymerized in solution in a batch reactor using AIBN as initiator. The solvent is ethyl acetate and the contents are maintained at 60°C. The reactor is initially charged with 75% by volume MMA, 25% by volume ethyl acetate, and enough initiator to achieve a rate of 0.05 mol/L. Compute and plot (a) rate of polymerization, (b) heat of polymerization, and (c) number average molecular weight as a function of polymerization time.

DATA: \( k_{p0} = 170 \text{ L/mol.s} \); \( k_p^0 = 1.85 \times 10^7 \text{ L/mol.s} \); \( k_d = 7.5 \times 10^{-6} \text{ s}^{-1} \); \( k_p/k_d = 0.00014 \); \( p_M = 0.91 \text{ g/cm}^3 \); \( p_s = 0.85 \text{ g/cm}^3 \); \( f = 0.5 \)

PROBLEM 3: Redo Problem 2 using the following gel-effect functionality for the termination rate constant: \( k_1 = k_p^1 \) for \( x \leq 0.36 \); \( k_1 = 0.1296(k_p^1x^2) \) for \( x > 0.36 \).

PROBLEM 4: Find the reactor volume, total flow rates, and average residence time to produce 1,000 ton/year of styrene-acrylonitrile bulk copolymer containing 28% (mole) acrylonitrile (365 days/year, 24 hours/day). If you need to make assumptions, state them clearly and justify them. Assume that the total conversion in 60%.

DATA: \( \eta_1 = 0.41 \); \( \eta_2 = 0.04 \); \( k_1 = 0.00014 \); \( M_p = 2500 \text{ L/mol.s} \); \( k_p^0 = 3 \times 10^5 \text{ L/mol.s} \); \( p_1 = 0.903 \text{ g/cm}^3 \); \( p_2 = 0.811 \text{ g/cm}^3 \); \( k_{10} = 10^5 \text{ mol/L.s} \); \( M_0 = 10^4 \text{ g/mol} \); \( M_p = 53 \text{ g/mol} \). \( \eta = \text{styrene, } (1-x)^2 \text{ for } x > 0.85 \)

PROBLEM 5: Consider a CSTR free-radical polymerization operating at steady state. Using the following data, map out the possibilities for steady-state conversion versus residence time. How would you achieve 75% conversion? For results uniformity, consider a reactor operation of 365 days/year and 24 hours/day.

DATA: \( \eta_1 = 0.017 \text{ mol/L} \); \( M_p = 1.5 \text{ mol/L} \); \( k_p^0 = 3 \times 10^5 \text{ L/mol.s} \); \( k_p^1 = 3 \times 10^{-3} \text{ s}^{-1} \); \( k_{10} = 900 \text{ L/mol.s} \); \( f = 1 \)

PROBLEM 6: An isothermal polymerization is carried out at 100°C with a dual initiator system. After three hours of polymerization, the monomer conversion is 60% in a 40,000-liter batch reactor. (a) Calculate the total radical concentration at 60% conversion of monomer \( (k_p^1=10^5 \text{ L/mol.s}) \); (b) How long does it take to grow a polymer chain of molecular weight equal to 10^7 at 60% conversion? (c) Calculate the instantaneous heat generation rate at 60% conversion. Compare this with the value at zero conversion; (d) Calculate instantaneous \( M_n \) and \( M_w \) at 0% and 60% conversion; (e) The growth in \( M_n \) at high concentrations gives too broad a MWD. The solution is to use a chain transfer agent (CTA). Find the amount of CTA required to keep \( M_n \) almost constant over the conversion interval 0-60% given that \( k_p^1=10^5 \text{ L/mol.s} \). Compare \( M_n \) values at 0% conversion for cases with and without CTA.

DATA: \( I_0 = 2 \times 10^2 \text{ mol/L} \); \( I_{12} = 5 \times 10^4 \text{ mol/L} \); \( MW = 100 \text{ g/mol} \); \( -(\Delta H_p) = 17 \text{ kcal/mol} \); \( k_{10} = 10^7 \text{ L/mol.s} \); \( k_{11} = 10^{-5} \text{ s}^{-1} \); \( k_{12} = 10^{-4} \text{ s}^{-1} \); \( M_n = 10 \text{ mol/L} \); \( \eta = 0 \); \( p = 10^5 \text{ L/mol} \).

TABLE 8
Some Senior-Year Design/Research Projects

- Dynamic simulation of ethylene-propylene impact copolymers in a series of CSTRs
- Copolymerization kinetics of methyl methacrylate/vinyl acetate
- Terpolymerization kinetics of methyl methacrylate/vinyl acetate/ butyl acrylate
- Investigation of kinetics of \( \alpha \)-methyl styrene/methyl methacrylate at elevated temperatures
- Investigation of butyl acrylate homopolymerization at high conversions
- Modeling of suspension polyvinyl chloride reactors
- Educational uses of a general polymerization simulator package
- Injection molding of medical plastics
- Gel content in polyethylene/propylene sheets

Winter 1998

NOTE
As a point of information for the academic readers of this article, we are planning a series of short courses to assist chemical engineering academics who are teaching, or wish to teach, polymer-related courses at the undergraduate level. We welcome all communications from interested academics who would like to either attend these short courses or to give lectures on undergraduate courses in the polymer area that they have successfully given. ☐
PRACTICAL TIPS FOR GATHERING INFORMATION

SAIDAS M. RANADE
Consultant • Houston, TX 77079-2995

Engineers working in process plants are problem-solvers. They play a very important role in process-plant troubleshooting. For example, consider the following situation:

The quality of a product from a certain unit has been degrading for some time and for some “unknown” reason. You are a plant support engineer and you have been called upon to help. Your job is to identify the root cause, to quantify the business benefits of solving the problem, and then to suggest ways to eliminate the factors causing the problem.

What is problem-solving, and how does it begin? The verb “solve” comes from the root solve, which means “to loosen, release, or set free.” The word “problem” comes from the roots pro, meaning “forward,” and ballein, meaning to “throw or drive.” So, problem-solving is a process of proposing and considering questions in a way that throws or drives us forward toward greater freedom.11

In their entertaining book, The Universal Traveler, Don Koberg and Jim Bagnall define the seven stages of creative problem solving as “acceptance, analysis, definition, idea-ation, idea-selection, implementation, and evaluation.”12 Clearly, being aware of a problem’s existence is the first step. Gathering information about the situation is the next step. One can learn about the situation through literature and document searches, by direct observation, and by gathering information from people closest to the problem. This skill of gathering data from others is a critical success factor for all practicing engineers. Whereas gathering information from literature and the Internet is emphasized in most engineering courses, to the best of my knowledge, training in how to gather information from others is not offered.

The main objective of this article is to share some practical ideas on improving the speed and effectiveness of the process of gathering information from others. It is based on my experience in designing and conducting opportunity and support needs assessment surveys for process modeling in process plants. Although the article will focus on techniques for more organized information gathering (such as surveys and on-site visits), the principles illustrated are equally applicable to informal information exchanges. This domain of designing and conducting surveys has been developed extensively by social scientists. I will begin first by defining the prerequisites for effective information exchange and then I will provide specific guidelines on how to pose the right questions. The article will also include a brief discussion on how one might be able to use this information in a classroom setting.

KEY PREREQUISITES

Early in my career, I learned that communication consists of a message, a sender, a receiver, a medium, a context, feedback, and noise.13 For gathering information, the message is the “questions,” and the medium may be a printed survey or a face-to-face interview (i.e., spoken words). I have discovered five key prerequisites necessary for creating the right context, capturing the feedback, and minimizing noise.

Trust • This is the first prerequisite. Thanks to authors such as Peter Senge15 and Stephen Covey,16 discussions on trust and trusting are becoming more acceptable, even among hard-core engineers. Trust is the foundation of all effective communication. The survey recipients must clearly understand the purpose of the information exchange. They must know “why” the information is being requested and “how” it will be used.

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Chemical Engineering Education
their information will be used.\textsuperscript{7,8} It is the interviewer's obligation to pursue the truth and truly believe in doing everything to benefit the interviewees. Of course, trust cannot be mandated, and there are no shortcuts to building trust. Vendors of software and associated services have the challenging task of overcoming a history of "lack of trust" created by their industry—for example, customers do not believe in software release dates. Also, in dealing with process manufacturing plants, the issue of confidentiality of information is very important and must be explicitly addressed prior to any useful information-gathering session.

**Credibility and Respect** • The second prerequisite to effective information-gathering is the interviewer's credibility in the domain of the specific inquiry. People are more open to answering your questions if you have already established a track record, either with the site or the process or the field of inquiry (i.e., if they respect you). There are pros and cons to this phenomenon. You may be very talented and may have a novel approach to solving problems; but you may not be effective simply because you are new. Also, due to this emphasis on "credibility," it is very tempting to use the jargon of the business superficially to establish credibility, but experience has shown me that instead of attempting to appear knowledgeable, it is better to admit that you are new to the field.

**Effective Listening** • This is the third prerequisite. Honest and open exchange of ideas is possible only when you have a genuine interest in the views and opinions of the interviewees. One of the best definitions of effective listening comes from Dr. Stephen Covey. He equates effective listening to faithful translation. The main requirement to having a dialogue and not just a discussion is to be completely open to the outcome. This is at the heart of any true discovery process. The word "dialogue" comes from two Greek roots: \textit{dia}, meaning "through," and \textit{logos}, meaning "the word." It carries a sense of "meaning flowing through." The word "discussion," on the other hand, stems from the Latin \textit{discutere}, which means "to smash to pieces." Additional useful information on the topics of "Inquiry" and "The Art and Practice of Conversation" is presented in Ref. 5.

**Proper Timing and Setting** • This is the fourth prerequisite. One of the biggest challenges for engineers and operators in process plants is to make time available for surveys and audits. Hence, the surveys must be aesthetically designed and the participants should be given ample time to complete them. In a face-to-face information-gathering session, the room in which interviews are conducted should be comfortable and open, with several whiteboards and easels. During a scheduled plant turnaround, a plant is typically shut down for several weeks. This period is used to make major modifications to the process and to install new plant equipment. Many of these new items have to be ordered six to nine months in advance, and it takes about three to six months to develop detailed specifications for major items. So the best time to conduct opportunity assessments is about nine to fifteen months prior to a scheduled turnaround. In this manner, the recommended revamp-type projects can be implemented during the turnaround period.

**Gratitude** • This is the fifth prerequisite. It helps immensely if your demeanor conveys a genuine sense of gratitude toward those from whom you collect information. In today’s atmosphere, it seems that everyone’s agenda is full all the time, so even if you do not find some of the responses to be useful, it always makes sense to thank the interviewees or survey participants for their time. It is also important to publicly acknowledge any contribution made by others to the success of your projects.

**GUIDELINES FOR POSING QUESTIONS\textsuperscript{[7-9]}**

After having satisfied the above prerequisites, one may still not be effective in conducting surveys and on-site interviews. This is where the "science" of asking questions comes into play. The following quotes and events signify the importance of questions and questioning:

- "You can tell whether a man is clever by his answers. You can tell whether a man is wise by his questions.”
  
  ~ Naguib Mahfouz
  
  Winner, Nobel Prize for literature, 1988\textsuperscript{[11]}

- When Richard Feynman was a child, his mother asked the future Nobel Prize winner the same question every evening at the dinner table: "What did you ask at school today, Richard?" (Feynman won the Nobel Prize for physics in 1965.)\textsuperscript{[11]}

- Hammurabi of Babylon changed the course of history by changing the representation when dealing with the problem of an inadequate water supply. Instead of asking how to get the people to the water, he asked how to get the water to the people. This led to the invention of canals.\textsuperscript{[10]}

Creation of the proper context is necessary for both printed surveys and on-site interviews. In a printed survey, the content and the order of the questions must be carefully selected. In a face-to-face interview, in addition to the choice of words and their sequence, proper tone of your voice plays a very important role.
I will begin with a brief discussion of different types of questions. Then I will provide guidelines on wording and maintaining a flow for the on-site interviews.

**Types of Questions**

In his book *Just So Stories* (1902), Rudyard Kipling (who won a Nobel Prize for literature in 1907) had this to say about types of questions: “I keep six honest serving men. They taught me all I know. Their names are What and Why and When and How and Where and Who.” The “how”-type question is the most open-ended. The “why”-type question may put the interviewee on the defensive. At some point in time, the questions beginning with “why” are essential to finding the cause of the problem; initially they may not be very effective, however.

Yet another method of classification also results in six types of questions. They are questions pertaining to experience/behavior, opinions/values, knowledge, feeling, sensory, and background (or demographics). For each type of question, one can ask about the present, the past, or the future.

Questions pertaining to experience or behavior or actions are easy to answer and should be used first. Sensory- and background-type questions are mundane and should be dealt with toward the end of the on-site interview. Questions pertaining to participants’ opinions/values and knowledge are very important for identifying symptoms and causes of problems, but they require proper context-building prior to their use. It is important to gauge the level of an individual’s knowledge about a given situation without making it seem that you are testing them. Engineers, in general, tend to shy away from “feelings”-type questions and, hence, they should be kept to a minimum.

For the time-frame, it is always appropriate to start from the present and then move to the past and then to the future.

**GUIDELINES ON PROPER WORDING**

**Basics**

- First, ask truly open-ended questions. “How satisfied are you with the performance of this heat exchanger?” may seem like an open-ended question, but it is not. Second, it is important to ask a “singular” question (i.e., refer to only one idea per question). A good question should be relatively short, clear, and unambiguous. Do not run a string of questions together. If you want to ask a string of related questions, then ask one at a time and get a response before proceeding. The question, “How often do you measure the pressure drop across this exchanger, how good are the measurements, and do you know the cause of the sudden increase in the pressure drop?” should be split up into three separate questions.

The third basic rule is to use the terminology and language of the interviewee or survey-recipient. Be careful of acronyms such as QIT, BIP, PIP, etc., because they may have different meanings at different plants. If you do choose to use acronyms, it is always beneficial to define them.

**A Few No-No’s**

- In the beginning, avoid questions that result in “yes” or “no” responses. The whole idea is to get the participants to “open up.” Also, avoid “why” questions in the beginning. From our childhood, we have been conditioned to associate some type of blame with the word “why.” (“Why” did you break this vase?) The objective of gathering information from others is accomplished when you make them feel comfortable about the situation and encourage them to have a dialogue with you.

**Proven Techniques**

- Presupposition-type questions are good. For example, “What is your most important idea regarding the cause of fouling?” This question presupposes that the interviewee is capable of having several good ideas about the cause of the problem. Questions pertaining to tough topics or questions that seem too direct can be softened considerably either by role playing (i.e., putting yourself in a new role in the question) or by simulation (i.e., putting the interviewee in a new role in the question). Rather than asking “What do you do in the plant in the morning?” ask, “If I were your colleague accompanying you in the plant, what would I observe?” And, instead of asking a unit engineer, “What are the goals of the entire plant?” try, “If you were the plant manager, what would be your top priorities?”

**Keeping the Flow**

- It is very important to keep the on-site interviews flowing smoothly. This depends on several factors. Establishing rapport with the individual and maintaining neutrality toward the information they provide are very important steps for keeping the flow. It always helps to make transitions smooth rather than abrupt by making specific announcements before the transitions. Prefatory statements such as, “The next question may seem a bit vague,” are very useful to ensure that the interviewee is not under undue pressure to look for a precise answer. Elaboration, clarification, and contrast-type probes are very useful in getting some individuals to talk. Of course, thanking the interviewee for providing a response to a tough question is also effective in keeping the flow of the process. In general, it is very hard to get engineers to converse openly with you, but occasionally you will come across individuals who try to monopolize the conversation and will not stop talking. In such cases, it is important to emphasize, in a conversational tone of voice, that everyone’s time is important. The flow of the process can be easily disrupted by long-winded or irrelevant comments.

**CLASSROOM APPLICATION OF THIS MATERIAL**

One easy way to make students aware of the issues involved in gathering information from others is to ask students to read this article and spend about an hour discussing the topic in the classroom. As an additional homework assignment, you may ask students to watch the 1996 Twen-
tieth Century-Fox movie, *Courage Under Fire*, which clearly demonstrates that the same event (or a problem) can be perceived very differently by different people. Since the right psychology and information may not exist readily in most chemical engineering classrooms, the only way to directly practice the techniques prescribed in this article is by simulating a few real-life situations in a classroom setting and requesting students to play specific roles. One such approach, which requires a fair bit of preparatory work, is described in the Appendix.

**CONCLUSION**

Engineers and managers are problem solvers. An important step in identifying and defining problems involves gathering data. Since every situation is unique, it always helps to gather information about a situation from the people who are closest to it. The techniques for gathering information from others are very important for process-plant troubleshooting and are not emphasized enough in formal chemical engineering education.

The main point is that one will be able to easily acquire useful information from others by ensuring that the prerequisites such as trust, respect, effective listening, proper timing, and gratitude are met and following the guidelines for correct wording, sequence, and tone of the questions. Practicing the techniques without the prerequisites is possible, but only results in manipulation and deception and should be avoided at all costs.

**ACKNOWLEDGMENT**

The opinions expressed or implied are those of the author and do not represent the views of AspenTech.

**REFERENCES**


**APPENDIX**

An Experiment for Testing the Ideas in a Classroom Setting

**Preparation** • At the beginning of the experiment, divide the students into groups of five. Provide each group with a handout or script describing a specific situation. Examples of such situations include safety incidents, environmental excursions, product quality problems, etc. You may use the published case studies from books, such as those by Lieberman,[12] Saletan,[13] etc., to create the specific scenarios. On each team, assign one of the following roles to each student

- Operator
- Plant Engineer
- Tech-Support Engineer from a Central Group
- Plant Manager
- Chemist

**Assignment** • To identify, define, and solve problems faced by all the other teams.

**Rules** • Give students about four weeks to complete the assignment. Request that the students

- Not reveal the actual script or handout to anyone outside of their team
- Play the assigned roles as faithfully as possible
- Only answer the questions being asked while remembering the mindset of the role they are playing
- Document their strategy for gathering the required information
- Document their feelings, thoughts, and any other reactions to the mode of inquiry used by each of the other teams.

**Criteria for Grading**

- Number of problems identified
- Number of problems solved
- Nature of the means used to obtain information
- Impact on the feelings of others during the process of gathering information
- Quality of the document describing the strategy used to acquire information
- Quality of the document describing the feelings and thoughts during the inquiry by other teams.
ADVICE FROM AN OLD-TIMER

W. DAN MACLEAN
Pinnacle Technology, Inc. • Lawrence, KS 66044

Process engineers, such as myself, who are approaching retirement or are at an age where "you can see it from here," probably received their undergraduate training in the 1950s. As we consider the prospect of retirement, or edge into it through part-time work or consulting jobs, it is interesting to consider how we differ from today's graduate.

There is little question that today's graduate is better equipped with the "tools of the trade" and better prepared to be immediately useful. But it can be argued that my generation spent an apprenticeship doing hand calculations that were more productive. For example, hours, if not days, were spent checking a heat exchanger design by hand, giving us a better feel for the variables involved than doing computer iterations would. But time soon evens everything out.

So, what can my generation pass on to new process engineers? Perhaps some rules-of-thumb that have been useful, or some guidelines for good practice, or some judgmental discernments that we have learned through unfortunate experiences. What follows are some of the rules and guidelines that have proven useful to me over the years.

STREAM EFFICIENCY

The stream efficiency, or annual on-stream operating time, is a key factor in successfully operating any chemical plant. Plants are designed to run on gallons per minute, or pounds per day, or barrels per stream day. But cash is generated and investors are rewarded from tons per annum, or pounds per year, or barrels per calendar day.

A key number to remember is 8760—the number of hours in a year. In a perfect world that is error and maintenance free, a plant would produce in a year 8760 times what it could produce in an hour. But allowing for a two-week annual maintenance shutdown and an unscheduled outage of one day a month, the operating hours in a year are actually 8136, for a stream efficiency of 93%.

In actual practice, a promise of more than 8000 operating hours in a year (or a stream efficiency of 91%) is highly suspect. Oil refineries that are well run and well maintained show that stream efficiencies in the 90s are difficult to achieve. The refining industry as a whole probably operates with a stream efficiency in the mid-to-high 80s.

Projected high stream efficiencies often stem from massaging the numbers to improve a project's economics, and "name plate" capacities are probably derived from a 72-hour test run, or whatever was contractually agreed upon at the beginning. Remember, though, that the real test run is the 8000-hour test. One should use 8000 operating hours per year as the goal, even when giving appropriate consideration to feed outages, power interruptions, changing product grades, etc.

ECONOMIC ANALYSES:
TOP LINE VS. BOTTOM LINE

There are many excellent guides to preparing economic projections for a new project. For the most part, these guides focus on developing the "bottom line," i.e., net profit, cash flow, payback, etc. That is what owners and investors want to see.

Much useful information, however, can be obtained from an analysis of the "top line," i.e., the total sales generated. One should look at sales generated per dollar invested in much the same way as stock analysts look at a company's sales-per-share. How many times per year the sales "turn over" the capital invested can lead to a good appreciation of a project's risks and rewards.

Assume annual sales per invested dollar are substantially greater than one; unless the project is the proverbial license

Dan Maclean graduated from the University of Toronto with a BASc in chemical engineering in 1954, and received his MASc in chemical engineering from Birmingham University (United Kingdom) in 1959. He worked for Celanese Corporation and for several oil refineries during his career, and since 1984 has had a wide range of consulting assignments, usually in the area of alternative fuels such as alcohol/gasoline blends and pyrolysis oils.
to print money, the margin per sales dollar is going to be thin. Examine the margin carefully. How firm is it? A small reduction in the margin could eliminate any profit. Is the operation a value-added one, such as refining crude oil where the margin is protected by a direct link between raw material and product prices? If a large volume of raw materials and products is involved, has sufficient attention been paid to materials-handling factors? Concentrate on the cost factors involved in the project.

HEAT EXCHANGERS

Without question, the most common mistake made in specifying heat exchangers is made by the conservative engineer anxious to supply adequate equipment who specifies too much area! By a unit that is too big, fluid velocities are reduced to less that 3 feet/second, transfer coefficients fall, and deposits build up in stagnant zones. Performance is poor and even, in some cases, inadequate.

Three feet/second is the absolute minimum velocity, shell or tube side, that should be considered. Providing the head required is a small price to pay for good heat exchanger operation.

A rapid way to estimate the number of tubes in a shell and tube exchanger is with the formula

$$N = C(L/P)^2$$

where

- $N$ = number of tubes
- $P$ = tube spacing, inches
- $L$ = "outer tube limit," inches
- $C$ = constant, 0.75 for square pitch, 0.86 for triangular pitch

The "outer tube limit" is 5/8 in. less than the shell diameter for fixed tube sheet or U-tube construction, and 1 1/2 in. less for floating head construction.

Assume 20-inch nominal shell diameter (19.2-inch inside diameter)

- 16-ft tube length, fixed tube sheet, 3/4-inch tubes on 1-inch square pitch
  - $N = 0.75 \times (18.575/1)^2 = 259$ tubes
  - Area $(259)(16)(0.196) = 812$ sq. ft.

or assume As above, but with 1-inch tubes on 1 1/4-inch triangular pitch

- $N = 0.86 \times (18.575/1.25)^2 = 190$ tubes
  - Area $(190)(16)(0.262) = 796$ sq. ft.

This formula neglects tubes lost due to multipass construction, impingement plates, etc.

PUMPS

The old adage, "All pump problems are suction problems," still applies. Design for low velocities in suction lines: 0.5 to 1 foot/second for boiling liquids, and 1 to 3 feet/second for non-boiling liquids.

Vortex breakers are often omitted or ignored. Cross or flat plate baffles, with a width of 2 to 4 times the nozzle diameter and a height of one-half the nozzle diameter are effective vortex breakers.

PLOTS AND COUNTERPLOTS

A company I once worked for operated some acetylation kettles in which sheets of cellulose (wood pulp) were acetylated with acetic anhydride. The kettles were jacketed with a recirculating brine to remove the heat of reaction. Brine circulation was controlled manually to prevent rising temperatures from degrading the cellulose and falling temperatures from reducing the reaction rate.

Varying temperatures, humidities, and time in storage of the cellulose resulted in varying moisture levels in the cellulose. This resulted in varying reaction temperatures and the recurring question—were we over- or under-controlling? Were we looking at random noise when the temperature wandered, or had reaction conditions actually changed?

Routinely, we plotted kettle temperatures to see to what extent we were diverging from set point. Next, we initiated a new plot for every five minutes, showing the cumulative extent to which temperature diverged from the set point. If the temperature was cycling randomly around the set point, this second curve would make an exaggerated cycle but would return to zero (see Figure 1).

If, however, reaction conditions had changed and a new equilibrium temperature had been established, the second plot would rapidly indicate this by going outside any bound-

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**Figure 1**

**There is little question that today's graduate is better equipped with the "tools of the trade" and better prepared to be immediately useful. But it can be argued that my generation spent an apprenticeship doing hand calculations that were more productive.**

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ary limits (see Figure 2). Boundary limits can be readily set after some operating experience.

The same kind of plot can be useful in any situation where you want to establish if a status quo situation or an existing trend line had been breached. They can be used alongside moving average plots in financial quotations.

Another plot I have found useful is the probability paper, both normal and logarithmic. A probability paper is most suited to record a series of events distributed around a mean where one wants to design for a certain fraction of the occurrence of the events. These events could be temperature

```
<table>
<thead>
<tr>
<th># of Trucks Loaded</th>
<th>Day number “M”</th>
<th># of Trucks Loaded, in order</th>
<th>[M/(N+1)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1</td>
<td>28</td>
<td>0.048</td>
</tr>
<tr>
<td>40</td>
<td>2</td>
<td>30</td>
<td>0.095</td>
</tr>
<tr>
<td>85</td>
<td>3</td>
<td>34</td>
<td>0.143</td>
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<tr>
<td>30</td>
<td>4</td>
<td>38</td>
<td>0.190</td>
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<td>67</td>
<td>5</td>
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<td>0.238</td>
</tr>
<tr>
<td>46</td>
<td>6</td>
<td>40</td>
<td>0.286</td>
</tr>
<tr>
<td>60</td>
<td>7</td>
<td>42</td>
<td>0.333</td>
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<tr>
<td>42</td>
<td>8</td>
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<tr>
<td>90</td>
<td>9</td>
<td>46</td>
<td>0.429</td>
</tr>
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<td>51</td>
<td>10</td>
<td>50</td>
<td>0.476</td>
</tr>
<tr>
<td>53</td>
<td>11</td>
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<td>0.524</td>
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<td>62</td>
<td>12</td>
<td>53</td>
<td>0.571</td>
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<tr>
<td>34</td>
<td>13</td>
<td>60</td>
<td>0.619</td>
</tr>
<tr>
<td>73</td>
<td>14</td>
<td>60</td>
<td>0.667</td>
</tr>
<tr>
<td>80</td>
<td>15</td>
<td>62</td>
<td>0.714</td>
</tr>
<tr>
<td>50</td>
<td>16</td>
<td>67</td>
<td>0.762</td>
</tr>
<tr>
<td>38</td>
<td>17</td>
<td>73</td>
<td>0.810</td>
</tr>
<tr>
<td>28</td>
<td>18</td>
<td>80</td>
<td>0.857</td>
</tr>
<tr>
<td>40</td>
<td>19</td>
<td>85</td>
<td>0.905</td>
</tr>
<tr>
<td>45</td>
<td>20 (N)</td>
<td>90</td>
<td>0.952</td>
</tr>
</tbody>
</table>

53.7 Avg.
```

or wind levels, ship arrivals, river flows, etc. As an example, consider daily truck loadings at a terminal. The number of trucks per day is tabulated by day “M” in Table 1. Next, arrange them in ascending order and divide “M” by (N+1), where N is the total number of days, and plot “M/(N+1) vs the number of trucks/day, or probability paper. The data aligns reasonably well (see Figure 3).

To satisfy the loading demanded four days out of five, or 80% of the time, inventory would be required to fill 70 trucks. If it was desired to satisfy the loading demanded nine days out of ten, inventory would be required to fill 85 trucks.

**LINE SIZING**

The guideline “1 pound per 100 feet” pressure drop can serve to size lines in a wide variety of situations. The tables in “Cameron Hydraulic Data,” based on the Williams and Hazen formula, form a conservative standard. Two points worth mentioning here are:

1) In long, large-diameter lines, hold the velocity down to a walking pace of 4-5 miles per hour, or 6-7 feet per second.
2) 1 1/2-in. sch. 40 pipe is the smallest size that will span 15-to-20-foot pipe racks without intermediate support. Operators often climb on piping to take readings, etc., so 1 1/2-in. pipe is the smallest pipe size that should be used for routine use.

These are some of the guidelines and rules-of-thumb that have been of value to me during my career. Perhaps this article will prompt other “senior” process engineers to share some of the experience they have gained during their careers. We seniors owe a lot to a profession that has rewarded us well, both personally and professionally. ☐
emphasize the book is strictly on fundamentals, particularly the general mathematical description of fluid motions and the presentation of solutions for important fundamental flow problems. The exposition is relatively abstract; little reference is made to applications, to experiments, or to observations of natural phenomena. In general, solutions to posed problems are obtained or outlined through exact analytical and numerical methods, primarily via singularity approaches or finite difference methods. This book contains a vast amount of detailed information, from the differential geometry of general surfaces in flow fields to the similarity solutions for Stokes flow near corners to the subtleties of the stability problem for inviscid shear flow.

The book begins with two excellent chapters on the kinematics of flows; of particular note are explicit general formulas for surface mean curvature and a collection of velocity fields determined by various vorticity distributions. The next chapter introduces stress and the equation of motion; nice features include a concise exposition of constitutive equations and a good discussion of vorticity transport; vorticity is a theme that receives a great deal of emphasis throughout the book. A brief chapter on hydrostatics follows, including many examples of the computation of static free surface shapes. Curiously, mean curvature is defined again, with no reference to Chapter 1.

Chapter 5 presents many of the classical exact solutions for viscous incompressible flow, including unidirectional flows, Jeffery-Hamel flow, stagnation point flows, and flows due to point sources.

Flow at low Reynolds numbers is the topic of Chapter 6. The primary emphasis is on singularity solutions of Stokes' equation, including a sketch of boundary-integral equation methods. A fairly detailed exposition of local solutions near corners is also given. Transient flow effects and the first effects of inertia are touched upon.

Chapters 7 and 8 describe irrotational flow and boundary layer theory, respectively. For irrotational flow, the basic results on force and torque exerted on a body in steady or time-dependent irrotational flow are described. Several pages are devoted to the use of conformal mapping for solving the Laplace equation. The chapter on boundary layers provides good coverage of the classical material.

Chapter 9 is a very nice chapter on hydrodynamic stability, containing the basic results for shear flow, free surface, capillary, and centrifugal instabilities, though perhaps too brief regarding centrifugal instability. Noteworthy is the discussion of the concepts of absolute and convective instability and their relationship. It would have been nice, however, to see some generic results about nonlinearity, such as a brief discussion of supercritical and subcritical bifurcation.

Chapters 10 and 11 focus on the solution of inviscid flow problems. Chapter 10 outlines the boundary integral equation approach to the solution of potential flow problems, while Chapter 11 describes vortex motion in inviscid fluids, with the goal of providing the framework for numerical solution of vortex dynamics problems. Chapters 12 and 13 provide a whirlwind tour of finite-difference approaches to solving convection-diffusion and incompressible flow problems. One attractive feature of this section is the presentation of the modified differential equations associated with some of the approaches, showing, for example, that the instability of the FTCS scheme for a hyperbolic equation is traceable to an effective negative numerical diffusivity. Finally, two convenient appendices contain basic results in vector calculus and basic numerical methods.

There is clearly a great deal of material covered here, and covered well. Nevertheless, the breadth and depth of coverage has its cost. The text occasionally becomes an extended list of formulas, solutions, or methods. This is fantastic as a reference; I have used it repeatedly myself and referred parts of it to several graduate students. It is not always ideal for teaching purpose though, as the means by which solutions are obtained is often given little motivation. Details of solution procedures are often not provided, and sometimes opportunities to impart physical insight are bypassed in favor of a terse, elegant, mathematical statement or argument.

The level of mathematical sophistication assumed is at least that of a first-year grad student in chemical engineering, preferably one who has already taken an applied math class covering linear algebra and elementary partial differential equations. Because of the mathematical level of this book, the abstract point of view, and the sole emphasis on fundamentals, it is not appropriate as an undergraduate text for chemical engineering students. Nevertheless, it is probably a text that any serious student of fluid dynamics would like to own, and it would provide a good text for either an introductory or advanced graduate course in fluids, depending on the topics chosen. The lecturer will need to fill in many of the motivations and solution details, but this is not a large price to pay for a text that outlines theoretical fluid dynamics as thoroughly as this one does.

In my opinion, this is a very important contribution to the textbook literature in fluid dynamics—a book I am happy to own and one that I would highly recommend to anyone working in theoretical fluid dynamics.
AN UNDERGRADUATE EXPERIMENT ON ADSORPTION

SHAMSUZZAMAN FAROOQ
National University of Singapore • Singapore 119260

Adsorption separation has become a major unit operation in the chemical process industry. Undergraduate chemical engineering students at the National University of Singapore receive about six hours of lectures on adsorption fundamentals and applications as part of the course Separation Processes II, offered in the third year of their study.

We have long felt there is a need for a suitable laboratory experiment that reinforces the basic design concepts. Since reliable equilibrium and mass transfer data are central to the design of an adsorption separation process, we have recently introduced an experiment in our third-year laboratory in which the students determine these parameters from breakthrough measurements in an adsorption column. During analysis of the breakthrough data, the students also develop a basic understanding of adsorption process dynamics.

EXPERIMENTAL APPARATUS

The experimental apparatus for breakthrough measurements, schematically shown in Figure 1, consists of a column packed with the adsorbent under study and a host of pressure and flow controllers that control the operating pressure and concentration of the adsorbate in the feed, respectively. Further details on the experimental apparatus and the adsorbent used are given in Table 1. The adsorbate is normally mixed with an inert carrier. The effluent stream is analyzed using a suitable detector to monitor the breakthrough of the adsorbate. The desorption response is measured by withdrawing the flow of adsorbate from the feed after the column has been saturated.

THEORY

A typical breakthrough response from a clean bed to a step change in adsorbate concentration in the feed is shown in Figure 2, where $c$ is the concentration at any time, $t$, and $c_0$ is the constant feed concentration. When the adsorbate concentration in the effluent equals that in the feed, it indicates that the bed has been saturated. Material balance over a saturated bed gives

$$\bar{t} = \frac{L}{v_o} \int_0^\infty \left(1 - \frac{c}{c_0}\right) dt = \frac{L}{v_o} \left(1 + \frac{1 - \varepsilon}{\varepsilon c_0}\right)$$

where

- $L$ = length of packed bed
- $v_o$ = interstitial feed velocity

**Figure 1.** Schematic diagram of the breakthrough apparatus. Further details are given in Table 1.
bed voidage

\[ q_0 \] equilibrium adsorbed amount corresponding to feed concentration, \( c_0 \)

A typical favorable equilibrium isotherm is shown in Figure 3. Henry’s constant will be measured in this study, which requires that the experiments are conducted in the linear (low concentration) range of the isotherm. Ratio of Henry’s constants of two adsorbable components is the primary measure of their separability.

It is important to note that here Henry’s constant is dimensionless, since it has been expressed as concentration ratios. Henry’s constant follows the Arrhenius Law of temperature dependence. The following equation is applicable for dimensionless Henry’s constant:

\[
K_0 = K_0 e^{-\Delta U_{o}/R_g T}
\]

where

- \( K_0 \) pre-exponential factor
- \( R_g \) gas constant in heat units
- \( T \) temperatures in absolute units

A semilogarithmic plot of \( K \) vs. \( 1/T \) should give a straight line with \( -\Delta U_{o}/R_g \) as the slope and \( K_0 \) as the intercept. The change of internal energy due to adsorption, \( \Delta U_{o} \), is related to:

\[ \Delta U_{o} = c_0 q_0 \]

**TABLE 1**

Details of the Experimental Apparatus Shown in Figure 1.

<table>
<thead>
<tr>
<th>Item</th>
<th>Manufacturer</th>
<th>Model/Part No.</th>
<th>Range/Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Flow Controllers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Helium line</td>
<td>Brooks</td>
<td>5850E (Controller)</td>
<td>0-10 l/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0151E (display)</td>
<td></td>
</tr>
<tr>
<td>• Oxygen line</td>
<td>J &amp; W</td>
<td>200-2002</td>
<td>built-in span adjustment from 1 cc/m to 1000 cc/m</td>
</tr>
<tr>
<td>Jacketed Adsorption Column (stainless steel)</td>
<td>Fabricated in the workshop</td>
<td></td>
<td>Pressure tested at 200 psi</td>
</tr>
<tr>
<td>• Length: 40 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Inner tube: 1 1/2 inch;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Outer tube: 2 1/2 inch;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Regulated Water Circulation</td>
<td>Poly Science</td>
<td>9101</td>
<td>10-95°C; 7 or 15 l/m</td>
</tr>
<tr>
<td>Oxygen Analyzer</td>
<td>SERVOMEX</td>
<td>572</td>
<td>Output: 0-1 V for 0-100% oxygen</td>
</tr>
<tr>
<td>Chart Recorder</td>
<td>Rikaderki</td>
<td>R-61A</td>
<td>100 mV full-scale setting was used</td>
</tr>
<tr>
<td>Pressure Gauge</td>
<td>WIKA</td>
<td></td>
<td>0-100 psi</td>
</tr>
<tr>
<td>On-Off Valves</td>
<td>Whitey</td>
<td>SS-41S2</td>
<td>1/8 inch</td>
</tr>
<tr>
<td>Plumbing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Stainless steel tube</td>
<td>Swagelok</td>
<td>SS-200-1-2</td>
<td>1/8 inch</td>
</tr>
<tr>
<td>• Male connector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Union</td>
<td>Swagelok</td>
<td>SS-200-6</td>
<td>1/8 inch</td>
</tr>
<tr>
<td>• Union elbow</td>
<td>Swagelok</td>
<td>SS-200-9</td>
<td>1/8 inch</td>
</tr>
<tr>
<td>Adsorbent</td>
<td>Carbon molecular sieve: Shirasigi MSG 3A from coconut shell. Provided by a local pharmaceutical company from the supply for their PSA nitrogen unit.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
to the limiting heat of adsorption, \( \Delta U_0 = \Delta H_0 + R_g T \). For calculating \( \Delta H_0 \) from \( \Delta U_0 \), the average temperature of the experimental range is used.

On the other hand, if the Henry’s constant is expressed in terms of adsorbate pressure (we denote it by \( K' = K/R' T \), where \( R' \) is the gas constant in pressure units), then its temperature dependence may be directly related to the heat of adsorption

\[
K' = K' e^{\frac{-\Delta H_0}{R' T}}
\]

The desorption breakthrough is obtained when a saturated bed is purged with inert. In the linear (and very low concentration) range of the isotherm, the adsorption and desorption profiles obtained at the same velocity are symmetric.

The system of equations that describe the dynamic response of an adsorption column is given in Table 2. Analytical solution to the set of equations is given by Lapidus and Amundson\(^{11}\) in the form of complicated infinite integral. In this study, numerical solution by the method of orthogonal collocation is used. (The collocation form of the model equations may be obtained from the author upon request.)

The input parameters for the model are:
- Column length, \( L \) → given (40 cm)
- Bed voidage, \( \varepsilon \) → given (0.35)
- Column radius, \( R \) → given (2.05 cm)
- Adsorbent particle radius, \( R_P \) → given (0.1 cm)
- Interstitial feed velocity, \( v_0 = u_0 / \varepsilon \) → \( u_0 \) is calculated from the flow rate measured during experiment (cm/s)
- Equilibrium constant, \( K \) → obtained from the breakthrough curve
- Peclet number, \( Pe \) → determined from available correlation

\[
Pe = \frac{v_0 L}{D_L}
\]

where \( D_L = 0.7 D_a + v_0 R_p \).

The molecular diffusivity of the adsorbate in the carrier is \( D_a (cm^2/s) \) and may be calculated from Chapman-Enskog’s equation.\(^{10}\) All known commercial adsorbents offer external film, macropore, and micropore resistances to the transport of the adsorbate molecules from the bulk phase to the interior adsorption sites. A linear driving force (LDF) rate model is used here to represent the transport across these resistances, \( k \) is the overall LDF rate constant. The LDF model approximates a distributed resistance to be confined in an equivalent thin zone. The individual resistances linearly add up to give the overall LDF resistance, \( 1/k \):

\[
\frac{1}{k} = \frac{R_p K}{3 k_f} + \frac{R_p^2 K}{15 D_e} + \frac{R_p^2}{15 D_e}
\]

The LDF model may be viewed as a lumped parameter model with the luxury of relating the overall constant to the more fundamental parameters that characterize the constitutive transport processes. The film mass transfer coefficient, \( k_f \), may be calculated from the following correlation proposed by Wakao and Funazkri:\(^{13}\)

\[
Sh = 2.0 + 1.1 Re^{0.6} Sc^{1.3}
\]

where
- \( Sh \): Sherwood number = \( 2 k_f R_p / D_m \)
- \( Re \): Reynold’s number = \( (2 R_p \rho_u / \mu) \)
- \( Sc \): Schmidt number = \( \mu / \rho D_m \)

### TABLE 2
Model Assumptions and Equations

(\( z \) is the axial distance; \( t \) is the time; \( P \) is the total system pressure; and \( \bar{q} \) is the total adsorbed amount. Other symbols are defined in the text.)

<table>
<thead>
<tr>
<th>Item</th>
<th>Assumptions</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid phase component material balance</td>
<td>• Isothermal</td>
<td>(-D_T \frac{\partial^2 Y}{\partial z^2} + v_0 \frac{\partial Y}{\partial z} + \frac{1 - \varepsilon}{\varepsilon} \frac{R_T}{P} \frac{\partial \bar{q}}{\partial t} = 0)</td>
</tr>
<tr>
<td>Continuity condition</td>
<td>• The flow pattern is described by the axial dispersed plug flow</td>
<td>(P \neq f(z) \neq f(t))</td>
</tr>
<tr>
<td>Flow boundary conditions</td>
<td>• The frictional pressure drop is negligible</td>
<td>(D_L \frac{\partial Y}{\partial z} \bigg</td>
</tr>
<tr>
<td>Mass transfer between fluid and particle</td>
<td>• The mass transfer rates are represented by linear driving force rate expressions</td>
<td>(\frac{\partial \bar{q}}{\partial t} = k_f (\bar{q}^* - \bar{q}))</td>
</tr>
<tr>
<td>Equilibrium isotherm</td>
<td>• Linear isotherm</td>
<td>(\bar{q}^* = K_c = K_c Y)</td>
</tr>
</tbody>
</table>
The above correlation is particularly recommended as it was able to reconcile experimental data from a large number of sources.

\[ D_e = \frac{e_p \cdot D_p}{\tau} \]

where \( 1/D_p = 1/D_m + 1/D_K \)

The Knudsen diffusivity, \( D_K \) (\( \text{cm}^2/\text{s} \)), becomes important when collision of the diffusing species with the pore walls becomes significant in comparison to the intermolecular collision. Poiseuille flow and surface diffusion are two other parallel contributions to transport in the macropores. Poiseuille flow is neglected since the pressure range in which it becomes important will not be encountered in this study.

Surface diffusion occurs through the adsorbed layer on the macropore walls. This is commonly found to be important in homogeneous adsorbents, such as activated carbon, activated alumina, silica gel, etc. For composite adsorbents, such as carbon molecular sieve and pelleted zeolites, the adsorption capacity is mainly in the micropores; the macropore walls are practically inert and the condition for surface diffusion to occur does not arise. Therefore, surface diffusion is also neglected, since we will study the adsorption and diffusion of oxygen in carbon molecular sieve. Of course, in the chosen system, both molecular and Knudsen diffusion are much faster than the micropore diffusion and may be neglected as well. Nevertheless, these terms are discussed further in view of their wider conceptual importance as mechanisms of transport in porous media in general.

Knudsen diffusivity is given by

\[ D_K = 9700 \left( \frac{T}{M} \right)^{1/2} \epsilon_p \]

where

- \( \epsilon_p \) pore radius (\( \text{cm} \))
- \( T \) temperature (in absolute units)
- \( M \) molecular weight of the adsorbate
- \( \epsilon_p, \tau \) absorbent particle voidage and tortuosity, respectively.

A typical value for \( \tau/\epsilon_p \) is approximately 10.

Therefore, in the expression for mass transfer parameter, the micropore diffusional time constant, \( D_e / \epsilon_p^2 \), is the only unknown that is determined by matching the model solution for a breakthrough with the experimental response. Micropore diffusion is an activated process and follows Arrhenius-type temperature dependence

\[ D_e = D_{co} e^{-E/RT} \]

A semilogarithmic plot of \( D_e \) vs. \( 1/T \), known in the literature as the Eyring plot, will give the activation energy, \( E \), from the slope and the pre-exponential factor, \( D_{co} \), as the intercept. For some adsorbents, such as carbon molecular sieve, \( \epsilon_p \) cannot be measured explicitly. In such cases, \( D_e / \epsilon_p^2 \) is plotted against \( 1/T \), which yields \( D_{co} / \epsilon_p^2 \) as an intercept.

**EXPERIMENTAL PROCEDURE**

The study of adsorption and diffusion of oxygen in a carbon molecular sieve is chosen as the model system here. Helium is used as the inert carrier. The following set of instructions is provided to guide the students through the various steps of the experiment.

- The oxygen analyzer response should be checked for 0 and 100% oxygen. The output range is 0-1 V and is linear. The calibration curve for the mass flow controller used for the carrier gas is provided. The total mixed flow can be easily determined by analyzing its oxygen content.
- It is suggested that the interstitial feed velocity in the column and oxygen concentration in the feed are maintained between 5 and 10 cm/s and between 2 and 4%, respectively. The adsorption column should be bypassed during flow and concentration adjustments. The system gauge pressure should not exceed 0.5 bar. The effluent is analyzed using the oxygen analyzer.
- A chart recorder is used to record the analyzer signal. The chart speed and range setting must ensure sufficient resolution of the output signal from the oxygen analyzer as a function of time.
- Water (from a temperature-regulated tank) is circulated through the jacket of the column at the desired temperature. The measurements should be conducted at three temperatures in the range of 30 to 50°C. The choice of temperatures should be evenly spaced and at least 45 minutes must be allowed for the bed to attain thermal equilibrium with the circulating water. It is also recommended to move from low to high temperature.
- The bed should be purged with helium until the 0 V baseline is attained. This ensures a clean bed with respect to oxygen.
- Introduction of the oxygen step in the feed and switching the chart on at the desired speed must occur simultaneously.
- It is essential that the breakthrough curves be measured until completion.
- It is necessary to record the desorption breakthrough curve for at least one temperature in order to check linearity of the isotherm at the chosen concentration level.
- Other than the formal desorption run, the bed is regenerated by purging with helium and increase in temperature. The adsorption breakthrough measurement is repeated when the bed has been completely regenerated and has attained the new temperature.

**RESULTS AND DISCUSSION**

The students are required to include the following results in their report on the experiment:

1. Plot of \( c/c_e \) vs. time for adsorption and \( (1-c/c_e) \) vs. time for desorption on the same graph in order to check the symmetry.

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2. $K_0$, $\Delta U_0$, and $\Delta H_0$ values from the semilogarithmic plot of $K$ vs. $1/T$.
3. $D_{ao}/t_m^2$ and $E$ values from the semilogarithmic plot of $D_{ao}/t_m^2$ vs. $1/T$.

Typical plots are shown in Figures 4 through 6. The parameter values determined from these plots are also shown in the respective figures. The equilibrium constant is obtained directly from the mean residence time calculated by integrating the breakthrough curves, as discussed earlier. The mass transfer parameter is obtained by matching the breakthrough profiles with the model solution. The effect of the mass transfer coefficient on the model solution is shown in Figure 7. It is clear that the model solution is quite sensitive to the value of $k$. The students are reminded that several numerical techniques are available to determine the best-fit values. But students carry out all the necessary computations and calculations in the laboratory and, in view of the limited laboratory time, they are allowed to use eye estimation to decide on the best fit.

While using the above method to measure $D_{ao}/t_m^2$, it is extremely important to remember that all the dispersive effects in an adsorption column (namely, axial dispersion, external film, and intraparticle diffusional resistances) that are identified in the mathematical model have similar effects on the shape of the breakthrough curve. Therefore, these effects cannot be separated from a single experiment. Moreover, since the resistances are linearly additive, there is always a risk of misinterpreting the results. Hence, there is an inherent need to always ensure that the rate parameter under investigation is indeed the controlling factor of the process dynamics. Reliable accounting of other effects is also necessary when they are not completely negligible.

Estimation of external film and macropore resistances are more reliable than prediction of axial dispersion. Maldistribution of gas flow and extra-column effects contribute to additional axial dispersion unpredictable by published correlations. Agglomeration of small particles may also result in excessive axial dispersion (see reference 3 for a comprehensive discussion). All these possibilities were taken into account while designing the experimental system used here. In order to ensure proper flow distribution, the column size was chosen to satisfy the recommended column-to-particle diameter ratio. Furthermore, 1/8-inch tubes and fitting were used to minimize extra-column mixing effects. In spite of all these precautions, experimental verification is recommended to confirm that the associated dispersive effects are correctly estimated.

Although the available laboratory time is not sufficient to include such supporting experiments, the students do not remain ignorant on these matters. In addition to writing a general discussion on the findings, they are also asked to suggest an experiment to prove that the present system is micropore-diffusion controlled and to comment on the effect
of macropore size and operating pressure on the macropore resistance. These questions guide their thoughts to the following important points:

- For a micropore-controlled system, a reduction in the macroparticle size should not affect the mass transfer kinetics. Hence, when the k value remains unaffected by a change in the particle size, it serves as clear proof that the axial dispersion and macropore resistance are practically negligible. On the other hand, a variation in values estimated from experimental runs with different particle size and/or at different velocities will indicate that the secondary resistances are not negligible and their contributions have not been properly estimated.

- The importance of Knudsen diffusivity depends on the effective macropore size and is independent of pressure, whereas molecular diffusivity is inversely proportional to pressure and may affect the overall transport rate at a higher pressure.

CONCLUSIONS

This laboratory exercise introduces the students to the calculations of equilibrium and kinetic parameters for an adsorption separation process. The use of a dynamic model for the extraction of the mass transfer parameter provides a useful visualization of the role of this parameter in process performance. The simulation model can also be effectively used to illustrate in detail the numerical solution of a system of coupled partial differential equations. The consistency of results obtained by different groups is encouraging. Equilibrium capacity and mass transfer resistance of the chosen system are well suited for completing the required number of runs and necessary computations in one standard laboratory session of six hours.

REFERENCES


BOOK REVIEW: Batch Distillation

Continued from page 13.

Example 1.2 are easily misinterpreted. And there is a technical mistake in the calculation of the heat to the reboiler in Eqs. (2.13) and (2.17). The author ignores the energy required to vaporize the distillate product in the reboiler. Equation 2.13 should be $Q_R = \lambda (R+1)D$.

The graduate-level material starts in Chapter 3, "Column Dynamics," which derives the unsteady mass and energy balances. Then error, stability, and a summary of numerical integration techniques are presented. The need for an integration technique capable of handling stiff equations is clearly illustrated in Example 3.1. The chapter is completed with sections on start-up and approximate models. There are some parts that will confuse students. For example, the numbering of stages in Figure 3.1 does not agree with the equations, and derivation of Eq. (3.44) requires assumptions not mentioned in the text.

The author is clearly an expert on the application of shortcut (Fenske-Underwood-Gilliland) methods to batch distillation. Readers are told to "be careful in choosing the appropriate value for the light key and heavy key for successful use of this method," but how to be careful is not explained. This and other small mysteries will cause confusion. The modified shortcut method developed next requires lumping a number of plates into compartments. Other than comparison with an exact solution, no guidance is given on how to select the number of plates in each compartment. The last section on the hierarchy of models in the simulator will be very helpful to students using the simulator.

Chapter 5, "Optimization," describes objective functions, degree of freedom analysis, feasibility, and the general framework of solution methods. This chapter is quite general and would benefit greatly from numerical examples. Chapter 6 on optimal control problems builds on Chapter 5. This chapter would also benefit from numerical examples in addition to the derivation examples.

The last chapter analyzes azeotropic systems and columns with a middle vessel. Since most students will be unfamiliar with the analysis of steady state azeotropic distillation, more details on residue curve maps and synthesis of batch distillation systems would be welcome. The shortcut method is extended to binary azeotropic systems and simple ternary systems. Extension to more complicated ternary azeotropic systems would be welcome.

The index appears to be quite well done. An author index would be appreciated. The reference lists at the end of each chapter appear to include all the important historical and recent papers. The nomenclature list is quite complete, and the tables that summarize the equations after each theoretical development are helpful. The type is easy to read and there appear to be few typographical errors. Unfortunately, the figures are not of professional quality and are difficult to interpret. Many of the figures have multiple curves that are not labeled. When two theories are compared on the same figure, the reader needs to guess which is which. The curves are not smooth and it is often unclear if the wiggles are real or due to the plotting routine.

Every chemical engineering department should obtain a copy for their library's reserve section. Chapters 1 and 2 will be helpful as a reference for undergraduates doing laboratory or design projects on binary batch distillation. The remainder of the book will help graduate students and professors who occasionally encounter multicomponent batch distillation problems.
COMBUSTION SYNTHESIS
AND MATERIALS PROCESSING

• Student Exercises •

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The student exercises below are representative of those developed for the Yale graduate course, "Combustion for Synthesis and Materials Processing," described in the fall issue of CEE (page 228). Among other purposes, they demonstrate that rather simple but quite rational calculations can be made to estimate approximately how large a combustion reactor must be in order to produce, say, a metric ton of high-value product every hour. Such preliminary design calculations are prudent first steps before considering more detailed follow-on calculations. They also develop a young engineer's intuition and provide interesting CS/MP examples of the important role of the ChE core subjects: chemical thermodynamics, homogeneous/heterogeneous chemical kinetics, transport phenomena, separation processes, and chemical reaction engineering. All notation is that of the author (Ref. 7, loc. cit.). Educators interested in further CS/MP exercises can contact the author at Yale University or electronically via rosner@htcre.eng.yale.edu

EXERCISE 1

Consider the combustor volume required for sulfur spray combustion at 1.4 atm at the S(l) feed rate of 50 t/d.

a) If efficient S(l) spray combustors can be operated at volumetric chemical energy release rates, \( \dot{q}_{\text{chem}} \), of about 2 MW/m\(^3\), then what volume should be provided for a 50 t/d unit?

b) How does this average volumetric chemical energy release rate compare to that in a small oil burner for home heating? Or a gas turbine engine combustor (at 3 GW/m\(^3\) at 30 atm) when corrected down to 1.4 atm? (cf. Fig. 1, loc. cit.)

c) If the amount of excess air used is that required for the combustion product mixture to have a temperature near 1400 K, then what will be the mean residence time (ms) in such a sulfur burner?

d) Estimate the time required to heat up a 100 \( \mu \text{m} \) S(l) droplet from 415 K to 700 K if the liquid heat capacity is estimated as 0.28 cal/g-K and the density is 1.8 g/cm\(^3\).

e) Estimate the time required to burn a 100 \( \mu \text{m} \) S(l) droplet at approximately 700 K if the latent heat of S(l) vaporization is 0.42 kcal/g and the ambient conditions are \( \omega_{O_2,\infty} = 0.232, T_{\infty} = 350 \text{K} \).

f) What phenomena would lengthen the time required to completely convert all S(l) droplets beyond your estimates from parts “d” and “e” above?

g) Is the combustor volume provided in part (a) likely to be adequate in this case? What would be the next steps you would recommend before “cutting metal”?

EXERCISE 2

a) Does the successful growth of diamond films from gas mixtures containing CH\(_3\)(g) and H(g) at 1 atm on 1200 K surfaces shake your confidence in the value of thermodynamic principles to judge the feasibility of chemical syntheses, generally? (See reference 1, below.) Does combustion synthesis of diamond films under these conditions violate the second law of thermodynamics? Discuss the broader implications of this recent discovery.

b) Approximately 20 \( \mu \text{m} \) (volume equivalent) diameter diamond crystallites (grains) are grown from rich C\(_2\)H/O\(_2\) flames impinging on 1200 K solid targets at p=1 atm. How many carats are these? (1 carat = 200 mg). How do they compare to the 30-mg diamonds synthesized (since 1954) by GE Corporation at p = 30 kbar, T = 2200 K? To get a physical feel for this pressure, convert to the units: metric tons (force) / (mm\(^2\)).

c) Consider the phase equilibrium C(graphite) \( \leftrightarrow \) C(diamond) in the single element system: carbon, from the viewpoint of the Gibbs phase rule. How many state variables are needed to define this system?

d) We know that C\(_2\)H\(_2\)(g) can be commercially synthesized from the pyrolysis of methane, CH\(_4\)(g), via a partial combustion process at acceptable yields. It is interesting that diamond film growth is found to be possible via the
fuel-rich combustion of either C\textsubscript{2}H\textsubscript{2}(g) or CH\textsubscript{4}(g), but the maximum attainable growth rates (often expressed in microns/h) have been found to be larger for acetylene by factors of nearly 20. Considering the overall economics, how would you decide on which carbonaceous fuel to use if your goal is to grow commerically interesting diamond films?

**EXERCISE 3**

Consider the preliminary design (sizing) of a 25 t/d acetylene synthesis reactor (near-plug-flow, axi-symmetric) to operate at near-atmospheric pressure. Based on preliminary laboratory data, it appears that the partial oxidation of preheated methane using oxygen, followed by approximately 1 ms. cracking at about 1800 K (before a water-spray quench to 350 K) leads to a product stream with about 8 mole pct. acetylene vapor and, unavoidably, produces solid carbon soot at the rate of about 50 kg/t C\textsubscript{2}H\textsubscript{2}. Preheating both (unmixed) reagents to about 900 K is considered the highest safe temperature choice to avoid autoignition upstream of the burner block/flame-holder. Make a self-consistent preliminary choice of all essential dimensions in the course of answering the following specific questions.

**a)** If the overall stoichiometry of the partial combustion of methane is CH\textsubscript{4}(g) + (1/2)O\textsubscript{2}(g) → CO(g) + 2 H\textsubscript{2}(g), then estimate the individual O\textsubscript{2}(g) and CH\textsubscript{4}(g) mass flow rates (kg/s).

**b)** Before turning to the turbulent jet mixing-diffuser section, estimate the required dimensions of a stable burner/flame-holder, including the channel diameters, number of channels, and open area fraction. Also select the downstream “cracking chamber” dimensions. For these purposes use the following tentative estimates: flame speed, S\textsubscript{f} (rich CH\textsubscript{4}/O\textsubscript{2}) = 28 cm/s at 298 K, 1 atm; $\ell$ n = S\textsubscript{f}/d $\ell$ n T\textsubscript{e} = 1.86 for methane/air; (L/U)\textsubscript{cracking section} = 1 ms. What factors should govern the channel (hole) lengths? (cf. Fig. 4, loc cit.)

**c)** Is the heat of partial combustion [CH\textsubscript{4}(g) + (1/2)O\textsubscript{2}(g) → CO(g) + 2 H\textsubscript{2}(g)] sufficient to raise the preheated mixture of methane and oxygen from 900 K to the cracking temperature of 1800 K without the addition of auxiliary oxygen at the burner/flame-holder location? Tentatively, neglect the possibly appreciable heat losses to a (water-cooled?) burner/flame holder.

**d)** Estimate the heating value of the solid carbon removed from this unit if it could be recovered and burned to CO\textsubscript{2}(g).

**e)** What factors dictate the quench water-flow-rate requirement? What spray velocities and drop sizes should be used? (cf. Fig. 4, loc cit.)

**f)** How would your choices of dimensions change if you opted for a synthesis reactor operating at 5 atm? For this purpose, note that the effective order of the methane oxidation corresponding to previously observed S\textsubscript{e}(p)-data for combustion with air is about 1.4.

**g)** Returning to the turbulent jet mixing-diffuser section, can you provide a rough estimate (bound?) of the required length, the transverse dimensions (diameters) for the 1 atm device? For all of the above items, spell out and defend all further assumptions you introduce.

**EXERCISE 4**

The surface of one C\textsubscript{60} molecule contains 20 hexagons and 12 pentagons. Based on the presumption that the C-C bond distance in C\textsubscript{60} is close to that in the graphite crystal (1.42 Å) estimate

**a)** The surface area of one C\textsubscript{60} molecule.

**b)** The effective diameter of one C\textsubscript{60} molecule.

**c)** Use the result in part b to estimate the Fick molecular diffusion coefficient of C\textsubscript{60} with respect to CO\textsubscript{2}(g) at 2100 K and 100 Torr (via hard-sphere kinetic theory).

**d)** Compare the specific surface area (m\textsuperscript{2}/g) of C\textsubscript{60} to that of commercial activated carbon as well as flame soot (containing non-porous primary particles of 30 nm diameter). What conclusion(s) do you draw from this?

**e)** Extrapolating from the information provided in the recent review of Howard (1992), suppose that C\textsubscript{60} could be produced in a 100 Torr benzene/O\textsubscript{2} combustor at a yield of 0.5 pct. of the fuel carbon. If the burner C/O ratio is about 0.9, use the present costs of benzene ($/kg) and O\textsubscript{2} ($/std. m\textsuperscript{3}) to

1) Estimate the fuel cost per kg. of C\textsubscript{60} produced and O\textsubscript{2} cost per kg of C\textsubscript{60} produced.

2) Estimate the pumping cost per kg of C\textsubscript{60} produced.

3) Compare the sum of these costs to the actual present cost per kg. of C\textsubscript{60}.

4) Is a combustion process currently used (by Aldrich, Hoechst AG ...) to produce research quantities of C\textsubscript{60}? What intrinsic advantages would a combustion synthesis process have over rival (electric spark and laser pulse/graphite feed) methods?

**f)** Use the reported equilibrium vapor pressure of crystal-line C\textsubscript{60}(s) to estimate the frost point temperature of C\textsubscript{60} in the abovementioned synthesis flame. Is a partial sublimation separation method feasible for harvesting C\textsubscript{60} in this case?

**REFERENCES**

JUST A COMMUNICATIONS COURSE?
Or Training for Life after the University

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Today, many chemical engineering curricula include courses in strength of materials, electronics, heat and mass transfer, reactor engineering, plant design, economics, communication skills, etc. Competence and technical expertise alone, however, will not guarantee graduates (or, as a matter of fact, anyone) a job in today’s economy. We should not only teach our students the necessary tools to enable them to survive in a work environment but we should also assist them in their transition from the university to industry. While there are career placement services on almost every university, their success in helping students find suitable employment after graduation is usually limited.

Having noted these difficulties in the past, I felt a need to become more actively involved in assisting students to find employment. Our students are now being given an early opportunity, as part of a two-credit-hour course in “Communications and Information Systems,”(1) to learn more about technical report writing, oral presentation skills, computer applications, and life after the university.

Many publications have been written on the subject of developing good communication skills.(2,3) This paper discusses the techniques used to teach students the principles of critical thinking, communication skills, and up-to-date computer technologies.

Guido Bendrich joined the Department of Chemical Engineering at the University of New Brunswick after spending some nineteen years in various industrial settings throughout the world. He obtained a PhD from McMaster University in 1992. His teaching and research interests are in industrial plant design, cost estimation, plastics processing, developing communication skills, and education.

TABLE 1
Course Objectives (Short Version)

You will bring your own interests and we shall discuss how they may be incorporated into the ChE 1014 course. We have an academic responsibility also to ensure that we aim for certain learning objectives and, for this course, those objectives are as follows:

1. Development of communication skills through oral and written presentations.
2. Familiarization with current information technologies.

Learning Objectives
Learning at this stage of your education means the development of critical skills. In this course, therefore, you will be

- articulating facts, concepts, principles, and rules;
- problem solving in real life situations;
- using effective communication skills;
- interacting productively in small and large group settings; and
- enjoying yourself too!

The Tools
We shall select practical examples to illustrate the principles of critical thinking, communication skills, and up-to-date computer technologies. The main part of the course shall be centered around the area of “Job Hunting.” The following steps will not only describe the course structure in more detail but also present a possible application of the material studied to a real-life situation.

- Career Assessment - the most critical phase in the whole process
  We shall discuss the various aspects in the area of Critical Thinking Skills and how we can make good use of it at home, in school or in a work environment.
- Decision Making - all about choices
  In order to make educated decisions one must have access to pertinent information. We shall explore different ways of obtaining the necessary information, e.g. libraries, databases, and the Internet.
- The Résumé—a very effective marketing tool
  The development of a great résumé requires of computer technology. We shall familiarize ourselves with the use of various computer applications such as word processors, databases, etc.
- The Job Market
  You will present in a 10-minute oral presentation some detailed information on the industry of your interest. We shall explore the use of overhead transparencies and computer-based presentation techniques. In addition, you will be given an opportunity to summarize your findings in the form of a technical report.
- The Cover Letter
  The writing of cover letters, i.e., letters of transmittal, is an important part in an engineer’s working life. We shall learn about the various styles of cover letters.
- The Interview
  We shall reinforce our critical thinking skills, learn about active listening, observe and diagnose verbal and nonverbal messages, and, most importantly, learn how to handle problem (stress) situations. Practice interviews will assist in refining these skills.
- The Tale of a Success Story
  At this stage, the course is coming to an end. You have not only learned about various computer applications, literature searches, oral and written presentations, and critical thinking skills but, more importantly, you have had an opportunity to apply these techniques to different situations in your daily life.
### Critical Thinking Skills

S. R. Covey[4] discusses the four unique human endowments of imagination, conscience, independent will, and self-awareness. Imagination, as defined by Covey, is "the ability to envision, to see the potential, to create with our minds what we cannot see at the present with our eyes." This ability does not come naturally, but it can be learned. The Critical Thinking Skills segment of this course provides the students with insight in the decision-making process. Some of the techniques discussed in detail are ones described by Covey,[4] deBono,[6] and Butler and Hoey.[5] These techniques aid students in discovering more about themselves.

In one exercise, based on deBono's approach, each class participant is asked to imagine six colored hats. Each hat represents a role one's mind plays in the critical thinking process. By switching from one hat to another as one thinks about a topic, the learner is forced to look at the topic from a variety of perspectives.[5] For the exercise, the students start with six sheets of paper—one for each hat. They select a topic or problem that they would like to think about or work on. Each participant decides which of the hats would be good to start with and then works his/her way through all six, writing down notes on the thoughts that come to them with each hat. Table 2 identifies the six hats, their characteristics and some of the questions one should ask with each one.[5] The students may think of other questions as well.

If the learner has worked a problem through all six hats and has written down at least three points for each, he/she will know that all the major points in the critical thinking process were covered. Table 3 presents some sug-
gested career-related headings that may be used to explore the critical thinking process.

This and similar exercises will not only help the students learn more about themselves but they can also aid the students in identifying their long-term career objectives. A significant increase in self-awareness can be observed over the course of the term.

**Computer Applications**

In this part of the course various computer applications, such as word processors, spreadsheets, databases, e-mail and Internet tools, are introduced to the students. Guidance is provided through the use of slides, handouts, and extensive hands-on exercises.

**Obtaining Information**

Information Technology is the buzzword of the 90s, and in that vein, an in-depth summary called “The Retrieval of Information” is presented to the students. Among the topics discussed in class are library and CD ROM searches, organization of database systems, and “how to surf” the Internet.

Assignments in this section focus on topics such as “Retrieve information about injection molding of polymeric materials,” or “Retrieve the latest information in the area of pulp bleaching.” The search results are then reported, as discussed below, both orally and in the form of a written report. The added benefit of these exercises is that the students are, at the same time, also broadening their knowledge in the general area of chemical engineering.

**Technical Writing**

In this section of the course, topics such as technical writing and document layout are introduced to the students. The assignment topics (technical reports) are based on information retrieved in the Obtaining Information section, and in addition, the students are introduced to different types of résumés.

One approach that has proven to be successful (but by no means the only appropriate model) can be found in “The Job Hunting Guide.”

Excerpts of this document are shown in Table 4. Guidance is provided in the résumé development process through slides, handouts, and hands-on exercises. The most important part of this document is the Objective section. Here the writer addresses the very important issues of “What skill do I bring to this position?” and “What can I do for the Company?” The insight obtained in the section on Critical Thinking Skills will guide the participants in the development of this subsection.

**TABLE 4**

**The Résumé**

**A Very Effective Marketing Tool**

The next step, after having successfully completed the career-planning phase, is the development of a résumé. If developed properly, it can be a highly effective marketing tool. Its two main purposes are to advertise your availability and to supply information to the recruiter.

How should a résumé be prepared? Perhaps the most important thing to remember is that the format must capture the recruiter. It should enable the recruiter to quickly find the key points. Clear headings, off-white paper, and point format are desirable. Remember that you will have less than ten minutes to prove to the person that you are an exceptional candidate. Effective use of language, emphasis on achievements, and quantified experience are thus important aspects of a résumé.

There are three basic formats being used today. The most widely used and accepted format, the chronological style, lists your experiences in reverse chronological order. This style emphasizes your most recent achievements. The functional format lists the duties performed by category. With this style, it is harder for the recruiter to get an instant picture of the candidate. The third type, which is not widely used, is a hybrid of the chronological and the functional format styles.

What key information should a résumé contain? The following eleven categories should be included:

- **Personal Data** • The only data required are your name, address, and phone number. Your fax number and e-mail address are optional. One would not want to supply information such as religion, marital status, or citizenship. These are “knock-out” factors that may or may not be used against you. You do not want to limit your chances right from the beginning.

- **Career Objective** • There is some debate on whether or not this section should be included in a résumé. Unless the objective is written carefully, do not include it. This section should show what you can do for the company and NOT what the company can do for you. A sample objective for a person who has participated in a Co-Op Professional Experience Program could read: “To provide leadership in industrial research and development activities, where strengths in superior analysis of data, problem solving, innovation, and excellent communication skills will: design and develop new technologies, provide opportunities for technology transfer, train and motivate staff, and generate results consistent with organizational initiatives.”

- **Professional Profile** • This summarizes your professional experience in a few short sentences. The following could be used as a guideline: “Engineering experience relating to injection molding, process automation, and the modeling of PET resin drying processes.”

- **Education** • List your education in reverse chronological order. Do not include your high school education if you have a college or university degree.

- **Work Experience** • Describe all the relevant work experiences here. Use action verbs such as directed, developed, implemented, designed, and presented to describe your accomplishments. Do not forget to include your job titles, times of employment, and the names of your employers.

- **Selected Achievements** • This section should list a maximum of three work/education-related accomplishments in more detail.

- **Professional Development** • This category should include all professional development activities that you have undertaken outside of the standard engineering curriculum.

- **Scholarships** • List all your scholarships.

- **Professional Affiliations** • Are you a member of a profession organization? List it here.

- **Languages** • Indicate the languages you know and your level of competence. If you are fluent in English and can “get by” in Spanish, you should write “Fluent in English and functional in Spanish.”

- **References** • “Available upon request.” Do not include the names of your (three) references in your résumé. Prepare the list of references on a separate sheet to be used as a handout during the interview.
A significant amount of effort by the students is voluntarily directed toward the development of this document. This high degree of motivation may be attributed to the fact that they are doing something for their own benefit, i.e., they can apply these skills during their studies as well as in their life after university.

**Presentation Skills**

An emphasis on the development of presentation skills in universities has significantly increased over the past decade. In our course, each student is given the opportunity to make a formal presentation to the entire class twice during the term. In a short, three-minute presentation, topics such as "The use of NaCl in the pulp and paper industry" or "Recent developments in the area of power generation" are presented to the whole class. Also, a ten-minute presentation summarizes the results obtained in the "Obtaining Information" section. A detailed discussion on the presenter's performance is scheduled on a one-to-one basis. The Oral Presentation Evaluation Form (Table 5) serves as an aid in this process.

In addition to these "formal" presentations, the students participate actively in short exercises throughout the term. At the beginning of each lecture, one student, selected at random by the instructor, must summarize the previous class in about three minutes. This exercise serves two purposes: everybody comes to class prepared and it gives the students yet another opportunity to hone their presentation skills. In addition to the above described exercises, students enjoy frequently-held "one-minute" impromptu talks.

**Discussion and Listening Skills**

The way a person asks and answers questions impacts significantly on the working environment. Questioning is a valuable tool and is critical to the oral communication process. Many successful approaches have been described in the literature. The students learn about and practice how to ask, as well as how to answer, two basic types of questions: open-ended and closed-ended.

As the communication process suggests, for communication to be congruent, one has to clearly understand the other's frame of reference. The students gain this understanding by asking questions that will clarify and confirm the messages others are sending to them. After the students were encouraged to engage in discussions, they observe and diagnose the other's verbal and nonverbal messages. Through group exercises and continuous feedback (see Table 6), one observes significant improvements in
the students’ performance.

**Real Life Situations**

Employers emphasize that interpersonal and communications skills are as important as technical knowledge. Through group exercises, the students are given several opportunities to practice different interviewing situations. Learning how to ask questions, and learning how to answer difficult ones, does not come quickly. Practice makes perfect. The skills and knowledge obtained in this course help the students to overcome interview anxiety.

**DISCUSSION**

The purpose of this course is to help students hone their communication skills. In addition, the students will learn more about themselves and their goals. These techniques, tested and refined over many years, work well in both university and non-university environments. When the concept was first being introduced, there were comments from our students such as:

- **“This instructor is crazy. He is trying to teach us communication skills and at the same time he is asking us to learn more about ourselves!”**

- **“I am just a second year student. I can’t use this concept to go after technical summer jobs!”**

After a few students tried the approach, the following comments were made:

- **“I got a job using the communication skills and job hunting techniques that I learned in your class.”**

- **“Thank you for your efforts. My communication skills improved significantly.”**

Initially, the students have to learn how to overcome their fears. Active support by the instructor is the key in this process. Support begins with the instructor’s in-depth understanding of the course material and its adaptation to the specific learning environment.

This course, unlike ordinary lecture courses, requires a significant amount of student/instructor interaction outside the scheduled class time. During the course of the term, the instructor should have several private review meetings with each student. The focus of these meeting should be on working together to achieve the goals that were set out in the course outline. By answering questions, resolving problems, and emphasizing good communication skills, these meetings can help foster an understanding and a strong commitment of the learner to her/his chosen profession. The instructor’s responses during the meetings should be positive and supportive. This will help ensure that the established goals are successful and are harmonious with those of the rest of the class.

By the end of the course, the students have not only significantly enhanced their communication skills, which of course is our main objective, but they should have also gained an enhanced self-awareness that will help them along their chosen career path.

**CONCLUSIONS**

A course such as “Communications and Information Systems” can be taught through the application of real life situations. Although there are currently many discussions being held about the university’s role in today’s society, the author strongly believes that, if one strikes the proper balance between the economically driven goals (i.e., the education of marketable students) and the more traditional goals of the university (i.e., let’s educate great thinkers), this approach will serve the students well in the future. “Let us not lose sight of the results we seek to achieve as we focus of the process of providing relevant chemical engineering education for the 21st century.”

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**REFERENCES**

AUTHOR GUIDELINES

This guide is offered to aid authors in preparing manuscripts for Chemical Engineering Education (CEE), a quarterly journal published by the Chemical Engineering Division of the American Society for Engineering Education (ASEE).

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